Satellite Navigation Using High Definition Television Signals

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 Satellite Navigation Using High Definition Television Signals

by

Ryan E. Handzo

B.S. A.E., Georgia Institute of Technology, 2011

A thesis submitted to the
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Department of Aerospace Engineering Sciences

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Satellite Navigation Using High Definition Television Signals  
written by Ryan E. Handzo  
has been approved for the Department of Aerospace Engineering Sciences

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Date ________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.
Spacecraft operators can use a variety of observables to perform orbit determination throughout a mission. Currently the mission design community has an interest in both autonomous spacecraft operations and in crewed, cis-lunar space missions. Navigators are focusing on ensuring resiliency and redundancy for satellites in the event that a navigation system fails. A spacecraft navigation system that utilizes high definition television (HDTV) signals is explored in this thesis. Using HDTV signals as the source for navigation observables, a satellite navigator can perform orbit determination (OD), either as the primary navigation source or as a backup navigation system. HDTV signals provide strong orbital coverage due to their prevalence around the world. It is shown that due to the high transmission powers HDTV signals are broadcast the signals can be received by satellites out to cis-lunar environments. The ability to extract accurate timing information from the signals in real time is demonstrated at a low CPU resource draw through the implementation of field-programmable gate arrays (FPGA). With the timing extracted from the signals, simulations show that accurate OD for satellites in lunar distant retrograde and halo orbits can be performed using only HDTV signals. These simulations are performed using the DE431 planetary ephemeris, planetary gravity, and solar radiation pressure in both an extended Kalman filter and square root information filter. The full satellite state, range and range-rate biases, and spacecraft reflectance are all successfully estimated by the filters with the presence of errors in the models of the systems dynamics. Since these signals are broadcast around the world at all times, they provide a free signal source for a satellite to utilize at any time more navigation information is needed or a back-up navigation source is required.
Dedication

To the memories of Dr. George H. Born and Carl B. Truxel. They were incredible teachers, supporters, and mentors without whom I never would have made it to this point.

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Chapter 1

Introduction

Satellite navigation is traditionally conducted using dedicated ground based tracking stations, Global Navigation Satellite Systems (GNSS) signals, and Optical Navigation (OpNav), among other methods. These tracking methods have been applied to numerous situations and have demonstrated varying degrees of accuracy, down to centimeter accuracy with post-processing in the case of the Global Positioning System (GPS). GNSS tracking is the preferred method of orbit determination (OD) below the GNSS altitude. Tracking stations such as the Deep Space Network (DSN) are available for use above GNSS altitude while OpNav is preferred for orbits around small bodies such as asteroids. There is a growing interest in both autonomous spacecraft operations and in crewed, cis-lunar space missions in the space community. The growing interest in these orbits has led to increased demand for navigation services which can provide both resiliency and redundancy for satellites in the event that GPS or other current navigation sources become unavailable.

A Signal of Opportunity (SoOp) is a signal broadcast for uses other than satellite navigation that can be acquired by an orbiting satellite and leveraged for positioning. These SoOps densely populate the space environment and are available in orbits where traditional GPS navigation solutions are unavailable. SoOps could be broadcast from many sources into the orbital environment; these include terrestrially broadcast signals as well as signals from satellites already in orbit. Terrestrially broadcast signals that could be useful as SoOps include High-Definition Digital Television signals (HDTV), Cell Phone Provider broadcast signals, Radio signals, etc. These sources all broadcast powerful signals out into the terrestrial environment that could potentially be
used in the space environment for navigation. The following sections will briefly describe several current navigation systems used by satellites, followed by a discussion of the navigation solution developed in this work.

1.1 Current Navigation Methods

Several current navigation system currently employed by satellites are described here. These discussions include the GNSS systems as well as the DSN, NASA Near Earth Network, the French Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system, OpNav, and X-ray pulsar navigation (XNav).

1.1.1 GNSS/GPS

The most well known satellite navigation data source for users around the world is the Global Positioning System (GPS). GPS receivers use trilateration to determine position by solving for \(x\), \(y\), and \(z\) position error and timing error on the receiver. GPS satellites broadcast a variety of signals which are then picked up by a receiver on the ground and processed to form a position solution. The codes that GPS satellites transmit are the C/A code and P(Y) code. The C/A code, or the coarse acquisition code, broadcasts a 1,023 chip code at 10.23 MHz while the P code is a 773.3875 GB code broadcast at 10.23 MHz. Each satellite continuously broadcasts a pseudo random noise (PRN) code in these signals which can be used for autocorrelation purposes. These PRN codes are orthogonal to each other and are known as Gold codes. These Gold codes have very small cross-correlations which allow for code from multiple satellites to be extracted simultaneously from the same frequency band. In addition to the PRN codes, GPS satellites broadcast navigation data which contains all of the satellite ephemerides, almanacs, clock parameters, ionospheric models, and health and status of each satellite. The navigation data is transmitted at 50 bps. All of this data is broadcast using code division multiple access (CDMA) modulation schemes.

The GPS system has a 24-satellite nominal constellation with eight backup satellites. These satellites are in six orbital planes at a 55° inclination. Each satellite is in a semi-synchronous
orbit with a period of 11 hours and 58 minutes at an altitude of 20,200 km. GPS receivers use a pseudorange measurement to generate their state estimates. The receiver correlates the PRN code with an internal PRN generator, the correlation yields a measurement for the transmission time of the signal which in turn is used with the measured receive time of the signal to generate a pseudorange. In order to obtain the most precise possible timing on the GPS constellation, each GPS satellite carries four atomic clocks on-board. The satellites use either Cesium or Rubidium clocks along with the GPS master clock at the US Naval Observatory (USNO) to maintain precise time. The USNO uses the average time of approximately 30 cesium-beam frequency standards and another 12 hydrogen masers to steer the GPS master clock. The clocks on-board each satellite are monitored in comparison with the master clock in order to ensure they stay within allowable drift models, and are generally accurate to better than 40 ns. These drift models are then uploaded to the GPS satellites to be broadcast to the receiver as clock correction values in the navigation message. The GPS network can provide navigation accuracy for users better than 1 m.

GPS competition is slowly increasing with other constellations such as the Russian GLONASS, European Galileo, and Chinese Beidou systems being developed. As these systems come online, and increase reliability, there will be multiple options for navigation below the GNSS orbital regimes.

1.1.2 Deep Space Network

The most well known NASA tracking center is the Deep Space Network (DSN) The DSN is composed of three tracking centers located in Goldstone - CA, Canberra - Australia, and Madrid - Spain. The DSN is managed and operated by the Jet Propulsion Laboratory (JPL) in Pasadena, California. Each of the DSN stations provides the use of 34 m and 70 m parabolic antennae for use by satellites needing tracking and telecommunications throughout the solar system. Recently Voyager 1 has shown the DSN can provide telecommunications and tracking out into interstellar space using the DSN’s 70 m dishes. The DSN is a system that was designed primarily to assist in interplanetary missions, but it is also used for radio and radar astronomy as well. The DSN provides
seven different data types, which be described next, for internal use as well as for satellites and their operators. The seven data types are Frequency and Timing, Tracking, Telemetry, Command, Monitor, Radio Science, and Very Long Baseline Interferometry (VLBI).

The DSN uses hydrogen masers and cesium frequency standards to keep a primary and three secondary frequency standards. These frequency standards are then used to synchronize the timing between all DSN sites and the system control center at JPL. The accuracy of the DSN timing system is known to nanosecond levels and verified against the GPS constellation. The tracking segment of the DSN provides the option for a satellite to get 1-, 2-, and 3-way Doppler and 1-, 2-, and 3-way ranging measurements. The monitor system is an internal system that monitors the operation and performance of the DSN and its antennas. The radio science system measures information in a received signal such as scintillation, attenuation, refraction, etc. in order to measure the shape or asteroids/comets and characterize the atmospheres around both the Earth and other planetary bodies. Finally, the very long baseline interferometry (VLBI) allows the DSN to provide precise time and timing intervals between the three antenna arrays. DSN VLBI is also used to measure the Earth’s rotation and polar motion. The precision of measurements along with the high demand for time on the DSN leads to current costs on the order of $1,000 a pass and an additional $1,000 an hour for NASA users; these costs are higher for commercial customers.

The DSN has been used for both lunar and interplanetary satellite navigation. The DSN has been used by missions such as ARTEMIS to achieve navigation solutions of 400 m in position RMS and 2.4 mm/s in velocity RMS.

1.1.3 Near Earth Network

The NEN is composed of both NASA tracking centers and commercial tracking centers that contract with NASA. The stated goals of the NEN are:

(1) Providing services to customers identified in the Space Communications Mission Model.

(2) Providing services of sufficient type, quantity, and quality to meet customer mission re-
quirements.

(3) Providing services as efficiently (inexpensively) as possible.

There are sixteen tracking centers that make up the NEN that are all managed by NASA Goddard Space Flight Center. These ground stations provide a wide variety in both latitude and longitude coverage to satellites. The NEN provides tracking options to satellites during the launch, early orbit, on-orbit, and end-of-life portions of a mission. Tracking data such as 1- and 2-way Doppler, 1- and 2-way ranging, and angular measurements are available from the NEN. Communication can be performed in the X, S, Ka, UHF, and VHF frequency ranges using the NEN; Table 1.1 shows the IEEE radio frequency bands as defined by IEEE Standard 521-2002. Currently the NEN charges $435 per pass for the use of NASA owned tracking stations and higher costs for the use of the commercial stations that NASA has contracts with.

Table 1.1: Standard radar frequency nomenclature, as defined by IEEE Standard 521-2002.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>0.003-0.03</td>
</tr>
<tr>
<td>VHF</td>
<td>0.03-0.3</td>
</tr>
<tr>
<td>UHF</td>
<td>0.3-1</td>
</tr>
<tr>
<td>L</td>
<td>1-2</td>
</tr>
<tr>
<td>S</td>
<td>2-4</td>
</tr>
<tr>
<td>C</td>
<td>4-8</td>
</tr>
<tr>
<td>X</td>
<td>8-12</td>
</tr>
<tr>
<td>Ku</td>
<td>12-18</td>
</tr>
<tr>
<td>K</td>
<td>18-27</td>
</tr>
<tr>
<td>Ka</td>
<td>27-40</td>
</tr>
<tr>
<td>V</td>
<td>40-75</td>
</tr>
<tr>
<td>W</td>
<td>75-110</td>
</tr>
<tr>
<td>mm</td>
<td>110-300</td>
</tr>
</tbody>
</table>
1.1.4 Doppler Orbitography and Radiopositioning Integrated by Satellite

DORIS is a French spacecraft navigation system used to obtain position solutions on the order of 1 cm in accuracy.\cite{20,21} DORIS is used by the TOPEX/Poseidon, JASON-1, JASON-2, and JASON-3 missions among others. This system currently uses 58 transmission stations to broadcast dual-frequency signals to be used for high precision Doppler based spacecraft navigation. The navigation information is broadcast at 401.25 and 2036.25 MHz.\cite{22} In order to ensure the navigation observables are accurate enough for precise orbit determination (POD) each DORIS station uses ultra-stable oscillators. DORIS can be used either for determining a navigation solution on the ground using post-processing, or for autonomous navigation using the DORIS immediate on-board orbit determination (DIODE) system. By post-processing the DORIS data, orbit accuracy of 1 cm is possible. DIODE provides the capability for 10 cm orbit accuracy in real-time.\cite{23}

1.1.5 Optical Navigation

OpNav contains two main types of tracking. The first uses images taken from an on-board camera to perform target tracking and obtain a navigation solution.\cite{24} OpNav is currently used for missions orbiting a small body and provides accurate body-frame navigation solutions.\cite{25,26} By comparing images of a body to a known map of the body’s geographic features, a measurement from the satellite to the landmark can be obtained. This measurement provides relative position information between the satellite and the body it is orbiting. OpNav can track hundreds of landmarks in any given image which can provide the navigation filter with a wealth of data. OpNav has been used to obtain 1 m relative position accuracies around small bodies and will be used on missions such as OSIRIS-REx.\cite{27,28} OpNav can only provide relative position solutions so are only as accurate in inertial space as the estimated position of the body the spacecraft is orbiting.

The second type of OpNav is used when tracking an object of interest from the ground. Measurements of right ascension (RA) and declination are taken and used by a navigator to obtain an OD solution. The use of RA and declination for tracking purposes requires accurate knowledge
of the user/telescope on the ground in order to achieve accurate measurements.

1.1.6 X-Ray Pulsar Navigation

XNav uses observations of pulsars to obtain a navigation solution. Pulsars emit unique signatures in the radio, infra-red, visible, ultraviolet, x-ray, and gamma-ray spectrum. The unique signatures of a pulsar provide consistent, known, and measurable signals to a receiver. By observing multiple pulsars and using post-processing techniques on the resulting data a position estimate for a satellite can be obtained. Pulsars can provide position solutions on the order of 1 km of accuracy.

1.1.7 Linked, Autonomous, Interplanetary Satellite Orbit Navigation

Linked, Autonomous, Interplanetary Satellite Orbit Navigation (LiAISON) is a method of OD which uses satellite-to-satellite tracking (SST). LiAISON uses SST to obtain an absolute navigation solution for two or more satellites. If the satellites are in orbits where one has an observably unique size, shape, and absolute orientation then SST observations can be used as navigation observables for a filter to obtain the orbits of the spacecraft. The navigation observables would provide the absolute orientation of the satellite with the unique orbit and the relative position of all other satellites in the system. Since the absolute position of one satellite is known the absolute positions of the remaining satellites can be obtained from the relative position information.

1.2 Motivation

A spacecraft navigation system that utilizes high definition television (HDTV) signals as a SoOp is explored by this research; the resulting navigation system is referred to as HDNav. The use of HDNav as an alternative, back-up or replacement for satellite navigation is an option being considered here.

The use of SoOps for terrestrial navigation in the absence of Global Navigation Satellite System (GNSS) solutions has been explored before. Several different navigation methods using
HDTV signals have been studied including using transmission tower watermarks,\textsuperscript{37} using synchronization codes in the signal,\textsuperscript{38,39} and using time of arrival (TOA) solutions from tower transmissions.\textsuperscript{40,41} Literature on terrestrial navigation methods utilizing HDTV signals have studied numerous challenges, such as signal interference from co-sited and closely positioned translators.\textsuperscript{42} The identification of transmission towers in a mobile environment using the Transmitter Identification (TxID) system found in North American television standards\textsuperscript{43} has shown that radios receiving HDTV in mobile/dynamic environments, outside of the design specifications for the HDTV transmission system, can still extract TxID information from the signal.\textsuperscript{44} It has also been shown that sub-nanosecond performance for relative time transfer is possible using HDTV signals in North America.\textsuperscript{45}

This prior work indicates that HDTV can be leveraged as a strong navigation data source for terrestrial use. If it can be demonstrated that these same techniques and procedures can be used for on-orbit satellites, then HDNav becomes a viable candidate for any future mission in the Earth-Moon system, whether as an alternate, back-up or replacement system. The concept of using HDTV signals as a navigation data source for orbit determination has yet to be studied in detail.

1.3 Thesis Organization

Chapter 2 discusses the feasibility of using HDNav for satellite OD. These studies investigate both the orbit coverage provided by HDTV signals and an analysis of the broadcast strength of the signals. The studies focus on cases using only the ATSC signal structure and on cases using all of the signal structures used around the world.

Chapter 3 describes a transmission facility used for broadcasting HDTV signals. This chapter looks at the equipment found in such facilities and how an HDTV signal is formed and broadcast. It also studies the redundancies broadcasters use in these facilities in order to ensure a continuous broadcast to customers.

Chapter 4 develops the signal processing algorithms needed to extract timing information from an ATSC HDTV signal. The chapter begins by discussing timing extraction techniques on
perfect simulated signals. This is then followed up with a discussion on how to use these techniques on signals in real-time. The use of these algorithms for both post-processing HDTV data and real-time data processing is demonstrated.

Chapter 5 discusses the results of experiments performed to further test signal timing extraction. This chapter begins by discussing small-body aircraft flights that were performed to evaluate signal strength and timing extraction. It then describes the results from a high-altitude weather-balloon test performed to evaluate timing extraction methods in sub-orbital environments.

Chapter 6 investigates how well sequential estimation filters perform OD for satellites in a variety of lunar orbits. These studies are performed for both an extended Kalman filter and a square root information filter. The simulation environment is described followed by a discussion on the performance of the filters.

Finally, Chapter 7 provides concluding remarks and summarizes important findings. Potential directions for future research in these topics are also discussed.
Chapter 2

The Feasibility of Satellite Navigation using High Definition Television Tower Transmissions

In order to evaluate if it is possible for satellites to perform orbit determination (OD) with HDTV signals, both the ability of the satellites to receive the signals and how much coverage the HDTV signals provide to a satellite on-orbit must be studied. These factors will either allow for strong coverage profiles or possibly prevent a satellite from ever receiving a navigation observable. If HDTV signals can provide coverage to a large portion of an orbit, while simultaneously being broadcast at power levels strong enough to be received, then HDNav will have potential as a navigation method. These topics are the focus of this chapter.

2.1 HDTV Signals

HDTV signals are broadcast throughout the world; however, the coding schemes vary by country/region. These different standards include the Advanced Television Systems Committee (ATSC) standard, the Digital Video Broadcasting - Terrestrial (DVB-T) standard, the Brazilian Digital Television System - International (ISDB-T) standard, and the Digital Terrestrial Multimedia Broadcast (DTMB) standard, as illustrated in Figure 2.1. Both the orbit coverage provided by the ATSC standard alone, due to its use in North America, as well as the coverage provided by HDTV signals using the ATSC, DVB-T, and ISDB-T standards around the world are studied in this chapter.

In the USA alone, there are over 8,500 towers broadcasting HDTV signals at over 400 kW of
Effective Radiated Power (ERP). These signals are highly structured with strong synchronization segments that can be used to extract timing information. The ATSC standard also requires that signals are synchronized with each other and have timing accurate enough to be used for potential geolocation. With transmission towers spread widely around North America, an orbiting satellite will have a wide variety of towers from which to extract navigation information. When towers using the DVB-T and ISDB-T standards are included, as well, an orbiting satellite will be provided a wider geometry from which to collect navigation information.

## 2.2 Coverage Analysis

The coverage analysis studies how frequently and for how long a satellite is in view of the HDTV tower transmissions for a variety of orbits using only ATSC towers, located in North American and South Korea, and using ATSC, DVB-T, and ISDB-T towers, located globally. The coverage provided from ATSC towers is calculated in the following orbital regimes: low earth orbit (LEO), including the orbit of the International Space Station (ISS) and a Sun-Synchronous orbit, Molniya orbits, and lunar L1 orbits. Individual orbits are used to give an example of coverage provided, as well as studies that look at entire orbital regimes.

The transmission towers for this study transmit at greater than 400 kW of ERP and are chosen to provide a complete grid of tower locations across the ATSC, as well as DVB-T and
ISDB-T signal sources. These studies involving only ATSC signals include signals spread across the continental USA and Mexico, as well as a single tower in Alaska, a single tower in Hawaii, and a single tower in South Korea. In reality, there are many transmitting signals, but the scenarios studied here only include these individual towers for computation speed. This simplification will demonstrate the coverage provided by the towers, though not the true quantity of towers that may be in view to a satellite. The locations of the transmission towers chosen for this study can be seen in Figure 2.2 with towers following the ATSC standard displayed in yellow and towers following the DVB-T and ISDB-T standards in red. All ATSC tower information used in this study is obtained from FCC documentation. While the worldwide number of HDTV towers grows every year, this study attempts to model only the coverage of the full system and not the full system itself.

The satellite orbits used for these studies are propagated every 30 seconds for a three-day period. An elevation mask is applied for all satellite states where the elevation angle falls outside of a 5-55° range. This simplification is used to account for the transmission towers’ horizontally focused beam patterns, the uncertainty of signal strength at higher elevation angles, along with the effects of local topography potentially blocking a transmission at elevation angles below 5°.

2.2.1 Low-Earth Orbit

The coverage analysis for LEO revealed that a satellite in an ISS orbit can view at least one of the 33 ATSC towers used for the study 16.64% of the time. On average, when in view of a tower, the satellite is in view of 4.94 towers, out of the 33 used in this study. Figure 2.3 shows the number of towers in view, out of the 33 used in this study, at any given time in this ISS-like orbit over three days.

Figure 2.4 displays the ground track locations throughout the satellite’s orbit during which the satellite sees at least one transmission tower. For an ISS orbit, the satellite has continuous tracking coverage over North America and South Korea and loses tracking during the remainder of the orbit.
Figure 2.2: Locations of the 167 transmission towers used for the various coverage analyses. Towers displayed in yellow are ATSC towers, while towers in red are towers following the DVB-T or ISDB-T HDTV standards.

Figure 2.3: Number of ATSC towers, of the 33 used in this study, in view of the satellite at all times during an ISS-like orbit.
2.2.2 Sun-Synchronous Orbit

Sun-synchronous orbits are of great interest/value to many different scientific missions and are widely implemented. The orbital elements for the sun-synchronous orbit used in this study are shown in Table 2.1. The study shows that a satellite in an example sun-synchronous orbit can view at least one of the 33 ATSC towers used for the study 18.06% of the time. On average, when in view of a tower, the satellite is in view of 4.7 towers out of the 33 used in this study. Figure 2.5 shows the number of towers in view, out of the 33 used in this study, at any given time in this sun-synchronous orbit over three days.

Table 2.1: Orbital elements of the sun-synchronous orbit used in this study.

<table>
<thead>
<tr>
<th>Semi-major axis (km)</th>
<th>Eccentricity</th>
<th>Inclination (deg)</th>
<th>Right Ascension of the Ascending Node (deg)</th>
<th>Argument of Periapsis (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7036.493</td>
<td>$1.664 \times 10^{-4}$</td>
<td>97.901</td>
<td>317.135</td>
<td>83.485</td>
</tr>
</tbody>
</table>

Figure 2.6 displays the ground track locations throughout the satellite’s orbit during which
Figure 2.5: Number of ATSC towers, of the 33 used in this study, in view of the satellite at all times during a sun-synchronous orbit.

the satellite sees at least one transmission tower.

Figure 2.6: Ground track of a satellite in a sun-synchronous orbit when an ATSC transmission tower is in view.
2.2.3 Systematic Study of LEO Coverage

The coverage provided to a satellite in LEO is shown in Figure 2.7. The coverage is calculated over two days for circular orbits with varying inclination between 0 and 180° and with varying altitude between 250 and 1500 km.

![LEO orbit coverage - Altitude vs. Inclination](image)

Figure 2.7: Fraction of orbit covered by HDTV signals transmitting using the ATSC standard. Coverage is shown as a function of orbit altitude and inclination. 33 towers located across the USA, Mexico, and South Korea are used for this study. The red lines denote the thresholds for 0.05, 0.10, 0.15, 0.20, and 0.25 fractions of orbit covered.

It can be seen in Figure 2.7 that orbit coverage ranges from 0-28%, depending on the orbit of the satellite. A low-altitude-equatorial orbit will receive little coverage from ATSC towers, while a high-altitude orbit with an inclination between 40 and 60° will receive upwards of 28% coverage. The coverage is nearly symmetric between posigrade and retrograde orbits.

In addition to the 33 ATSC towers used for the coverage analysis, a secondary coverage analysis was performed using 167 towers from around the world including ASTC, DVB-T, and ISDB-T towers. This study assumes signals originating from towers using the ATSC, DVB-T, and ISDB-T standards are all available to the satellite. The HDTV towers following these three
main transmission standards are located in major cities around the world. Earlier in this chapter, Figure 2.2 shows where the DVB-T and ISDB-T towers are located in red. Figure 2.8 shows the resulting coverage provided by the towers.

Figure 2.8: Fraction of orbit covered by HDTV signals broadcast from towers all around the world. Coverage is shown as a function of orbit altitude and inclination. 167 towers located across the world are used for this study. The red lines denote the thresholds for 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 fractions of orbit covered.

Figure 2.8 reveals that this diversity in tower location provides the LEO satellite with coverage ranging from 23.95% to 88.70%. Orbits with a low altitude and polar inclination provide the least coverage while high altitude orbits with inclinations below $65^\circ$ provide the most coverage.

2.2.4 Molniya Orbit

Molniya orbits allow for the study of the coverage available from HDTV transmissions in a more elliptic orbit. The orbital elements of the example Molniya orbit used in this study are shown in Table 2.2. The study demonstrates that a satellite in a Molniya orbit can view at least one of the 33 ATSC towers used for the study 90.54% of the time. On average, when in view of a tower,
the satellite is in view of 11.44 of the 33 towers. The number of towers in view at any given time in this study is represented in Figure 2.9.

Table 2.2: Orbital elements of the Molniya orbit used in this study.

<table>
<thead>
<tr>
<th>Semi-major axis (km)</th>
<th>Eccentricity</th>
<th>Inclination (deg)</th>
<th>Right Ascension of the Ascending Node (deg)</th>
<th>Argument of Periapsis (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26521.912</td>
<td>0.748645</td>
<td>62.1292</td>
<td>18.559</td>
<td>286.381</td>
</tr>
</tbody>
</table>

Figure 2.9: Number of ATSC towers, of the 33 used in this study, in view of the satellite at all times during a Molniya orbit.

Figure 2.10 displays the ground track locations throughout the satellite’s orbit during which the satellite sees at least 1 transmission tower. Molniya orbits can see very different orbit coverage, depending on the right ascension of the ascending node (RAAN) of the satellite. Figure 2.11 exhibits the variation of orbit coverage seen by a satellite using the same 33 ATSC towers, over two days, in a Molniya orbit with varying RAAN values. A Molniya orbit can get as much as 93.91% coverage, and as low as 84.23% coverage in certain orbits.

The same analysis was performed using 167 towers spread around the world using the ATSC,
Figure 2.10: Ground track of a satellite in a Molniya orbit when an ATSC transmission tower is in view.

Figure 2.11: Fraction of orbit covered by HDTV signals transmitting using the ATSC standard. Coverage is shown as function of RAAN. 33 Towers located across the USA, Mexico, and South Korea are used.
DVB-T, and ISDB-T standards. A Molniya orbit sees as much as 99.65% and as low as 98.04% orbit coverage depending on the orbits’ RAAN from these 167 towers. This indicates that HDTV towers can provide near continuous navigation coverage for a satellite using a Molniya orbit.

2.2.5 Lunar L₁ Orbit

Lunar libration orbits, among other cis-lunar orbits, such as distant retrograde orbits, lissajous orbits, etc., are currently of interest to NASA and the scientific community. These orbits can provide staging points for future manned missions to Mars, as well as holding points for an asteroid for the asteroid redirect mission (ARM). The L₁ orbit studied for this case had a reference epoch of January 1st 2020, with a z-amplitude of 20,000 km. The study reveals that a satellite in a lunar L₁ orbit can view at least one of the 33 ATSC towers used for the study 88.18% of the time. On average, when in view of a tower, the satellite is in view of 12.4 of these towers. The number of towers in view, at any given time in an orbit, can be seen in Figure 2.12. The ground track locations throughout the satellite’s orbit during which the satellite sees at least one transmission tower can be seen in Figure 2.13. When ATSC, DVB-T, and ISDB-T standards were all used, the satellite experienced complete and continuous coverage, supporting the viability of HDNav as an alternative, back-up, or replacement navigation system.

2.2.6 Coverage Study Summary

The total coverage profile of the 33 ATSC towers for satellites in orbit is summarized in Table 2.3. The total coverage profile of the 167 HDTV towers around the world for satellites in orbit is summarized in Table 2.4. These studies provide evidence indicating that HDTV signals can provide satellites with navigation coverage throughout various orbital regimes. Using only the ATSC standard, a LEO satellite can obtain up to 28.73% of orbit coverage, while a LEO satellite tracking HDTV signals from ATSC, DVB-T, and ISDB-T can obtain up to 88.70% orbit coverage. For LEO satellites, the highest orbit coverage was found at an inclination between 50 and 60°. For LEOs, the coverage was seen to increase with orbit altitude.
Figure 2.12: Number of ATSC towers, of the 33 used in this study, in view of the satellite at all times during a lunar libration orbit.

Figure 2.13: Ground track of a satellite in a lunar L₁ orbit when an ATSC transmission tower is in view.
Table 2.3: Summary of the on-orbit satellite coverage provided from HDTV towers using the ATSC standard.

<table>
<thead>
<tr>
<th>Orbit Type</th>
<th>Percent of Orbit Covered</th>
<th>Average Number of Towers in View, Out of 33 Used for this Study.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISS</td>
<td>15.73</td>
<td>4.9</td>
</tr>
<tr>
<td>Example sun-synchronous</td>
<td>17.39</td>
<td>4.5</td>
</tr>
<tr>
<td>Example Molniya</td>
<td>90.54</td>
<td>11.4</td>
</tr>
<tr>
<td>Best LEO orbit</td>
<td>28.73</td>
<td>5.1</td>
</tr>
<tr>
<td>Best Molniya</td>
<td>93.91</td>
<td>23.4</td>
</tr>
<tr>
<td>Lunar L₁</td>
<td>88.18</td>
<td>12.45</td>
</tr>
</tbody>
</table>

Table 2.4: Summary of the on-orbit satellite coverage provided from HDTV towers, using all three standards, located across the world.

<table>
<thead>
<tr>
<th>Orbit Type</th>
<th>Minimum Percent of Orbit Covered</th>
<th>Maximum Percent of Orbit Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO</td>
<td>23.95</td>
<td>88.70</td>
</tr>
<tr>
<td>Molniya</td>
<td>98</td>
<td>99.75</td>
</tr>
<tr>
<td>Lunar L₁</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Molniya orbits could see up to 90.54% orbit coverage using only ATSC signals and near continuous coverage using ATSC, DVB-T, and ISDB-T signals. For lunar L₁ orbits tracking only ATSC signals provided up to 88.18% orbit coverage, while ATSC, DVB-T, and ISDB-T tracking provided continuous coverage for the satellite.

These results indicate that HDNav could provide reliable orbit coverage to satellites using HDTV signals for navigation purposes. The spread of HDTV towers around the world allow for HDNav to provide tracking coverage to a wide variety of orbits.

### 2.3 Satellite Link Budget

The carrier-to-noise ratio, received power, and power flux density are all link parameters that will be calculated for a satellite using HDTV transmissions. These parameters provide information regarding whether the signal will be visible to a receiver on-orbit, as well as provide insight into
the expected noise and biases found in the signals.

2.3.1 Free-Space Loss

The most significant loss in a signal between HDTV towers and an orbiting satellite is free-space loss, \( L_s \). Free space loss, calculated using Equation (2.1), is the attenuation of a signal during a line-of-sight transmission in free space.\(^{23}\)

\[
L_s = 20 \log_{10} \left( \frac{\lambda}{4\pi d} \right)
\]  

(2.1)

The parameters of Equation (2.1) include:

(1) \( \lambda \) is the transmitted signal wavelength.

(2) \( d \) is the distance between the transmit tower and the satellite.

The free-space loss for a LEO at an altitude of 1000 km is in the range of 148.4 dB, while the free-space loss for a GEO satellite is approximately 179.5 dB, and the free-space loss for a lunar orbiter is on the order of 200.0 dB.

2.3.2 Atmospheric Attenuation

HDTV transmissions are mainly in the ultra-high frequency (UHF) regime, between 470 and 890 MHz; as such, atmospheric attenuation of the signal will have a noticeable effect. This attenuation source needs to be modeled because it adds noise to the captured signal, limiting its effective range. The atmospheric attenuation is calculated here using a curve-fitted atmospheric model, like that used by the International Telecommunication Union (ITU), instead of a more computationally expensive layer-by-layer approach.

The curve-fit equations are built for use below 20 km of altitude; they lose accuracy above this threshold. The absolute difference between the layer-by-layer equations and the simplified curve-fit equations is less than 10%.\(^{23}\) Since the atmospheric absorption has a small overall effect
on the order of $5 \, dB$ for ATSC frequencies on the received signal strength, the simplified curve-fit equations are considered reasonable for use in this study. The curve-fitted attenuation model used includes the effects of dry air, water vapor, clouds and fog, as well as rain.

The first atmospheric attenuation source that the model addresses is the specific attenuation due to dry air and water vapors. The dry air attenuation effects, $\gamma_0$, can be calculated using Equation (2.2), while the attenuation due to water vapor, $\gamma_w$, can be determined using Equation (2.3).

$$\gamma_0 = \left[ \frac{7.2r_p^{2.8}}{f^2 + 0.34r_p^{2.16}} + \frac{0.62\xi_3}{(54 - f)^{1.16}t_f + 0.83\xi_2} \right] f^2r_p^2 \times 10^{-3} \quad (2.2)$$

$$\gamma_w = \left\{ \begin{array}{l}
\frac{3.98\eta_1 \exp[2.23(1 - r_t)]}{(f - 22.235)^2 + 9.42\eta_1^2} g(f, 22) + \frac{11.96\eta_1 \exp[0.7(1 - r_t)]}{(f - 183.31)^2 + 11.14\eta_1^2} + \frac{0.081\eta_1 \exp[6.44(1 - r_t)]}{(f - 321.226)^2 + 6.29\eta_1^2} \\
+ \frac{3.66\eta_1 \exp[1.6(1 - r_t)]}{(f - 325.153)^2 + 9.22\eta_1^2} + \frac{25.37\eta_1 \exp[1.09(1 - r_t)]}{(f - 380)^2} + \frac{17.4\eta_1 \exp[1.46(1 - r_t)]}{(f - 448)^2} \\
+ \frac{844.6\eta_1 \exp[0.17(1 - r_t)]}{(f - 557)^2} g(f, 557) + \frac{290\eta_1 \exp[0.41(1 - r_t)]}{(f - 752)^2} g(f, 752) \\
+ \frac{(8.3328 \times 10^4)\eta_2 \exp[0.99(1 - r_t)]}{(f - 1780)^2} g(f, 1780) \right\} f^2r_p^2.5 \rho \times 10^{-4} \quad (2.3)$$

The parameters of Equations (2.2) and (2.3) include:

$$\xi_1 = \phi(r_p, r_t, 0.0717, -1.8132, 0.0156, -1.6515) \quad (2.4)$$

$$\xi_2 = \phi(r_p, r_t, 0.5146, -4.6368, -0.1921, -5.7416) \quad (2.5)$$

$$\xi_3 = \phi(r_p, r_t, 0.3414, -6.5851, 0.2130, -8.5854) \quad (2.6)$$

$$\phi(r_p, r_t, a, b, c, d) = r_p^a r_t^b \exp[c(1 - r_p) + d(1 - r_t)] \quad (2.7)$$
\[ \eta_1 = 0.955 r_p r_t^{0.68} + 0.006 \rho \]  
(2.8)

\[ \eta_2 = 0.735 r_p r_t^{0.5} + 0.0353 r_t \rho \]  
(2.9)

\[ g(f, f_i) = 1 + \left( \frac{f - f_i}{f + f_i} \right)^2 \]  
(2.10)

\[ r_p = \frac{p}{1013} \]  
(2.11)

\[ r_t = \frac{288}{273 + t} \]  
(2.12)

Where:

(1) \( f \) is signal frequency in GHz.

(2) \( \rho \) is the water vapor density in g/m\(^3\).

(3) \( p \) is the atmospheric pressure in hPa.

(4) \( t \) is the atmospheric temperature in \(^\circ\)C.

Equations (2.2) and (2.3) yield the specific attenuation in dB/km of atmosphere through which the signal travels. Equation (2.13) is used to determine the total attenuation from dry air and water vapor, in dB, that the signal experiences.

\[ A_{\text{dry+water}} = (\gamma_0 + \gamma_w) r_{\text{atmosphere}} \]  
(2.13)

Geometrical relationships between a spherical Earth and the height of the stratopause show that the distance in km the signal passes through the stratosphere is equal to \( r_{\text{atmosphere}} \):
\[ r_{\text{atmosphere}} = \frac{2r_E \cos(\theta + 90^\circ) + \sqrt{(2r_E \cos(\theta + 90^\circ))^2 - 4(r_E^2 - r_S^2)}}{2} \]  

(2.14)

Where:

1. \( r_E \) is the radius of the Earth in km.
2. \( r_S \) is the radius of the Earth plus the height of the stratopause, in km.
3. \( \theta \) is the path elevation angle from the transmitting antenna to the satellite, in degrees.

Equation (2.14) is derived based on the troposphere contains appropriately 80% of the mass of the total atmosphere while the stratosphere, up to the stratopause, contains approximately 99% of the atmosphere, which is the effective range of these atmospheric attenuations. The stratopause can, on average, be assumed to be 50 km directly above any given location on Earth, assuming a spherical Earth.\(^{58}\) The stratopause can fluctuate in height, depending on different space-weather conditions observed around the Earth.\(^{59}\)

The next atmospheric attenuation source included in the model is the specific attenuation due to clouds and fog.\(^{60}\) The attenuation due to clouds and fog, \( A_{\text{cloud+fog}} \), can be approximated for all frequencies up to 1000 GHz, using a mathematical model based on Rayleigh scattering. Equation (2.15) is used to determine the total attenuation in dB expected to be experienced by the signal during its transmission path.

\[ A_{\text{cloud+fog}} = \frac{LK_I}{\sin(\Theta)} \]  

(2.15)

The parameters of Equation (2.15) include:

\[ K_I = \frac{0.819f}{\epsilon''(f)(1 + \eta^2)} \]  

(2.16)

\[ \eta = \frac{2 + \epsilon'(f)}{\epsilon''(f)} \]  

(2.17)
\[ \epsilon''(f) = \frac{f(\epsilon_0 - \epsilon_1)}{f_p \left[ 1 + \left( \frac{f}{f_p} \right)^2 \right]} + \frac{f(\epsilon_1 - \epsilon_2)}{f_s \left[ 1 + \left( \frac{f}{f_s} \right)^2 \right]} \] (2.18)

\[ \epsilon'(f) = \frac{\epsilon_0 - \epsilon_1}{\left[ 1 + \left( \frac{f}{f_p} \right)^2 \right]} + \frac{\epsilon_1 - \epsilon_2}{\left[ 1 + \left( \frac{f}{f_s} \right)^2 \right]} + \epsilon_2 \] (2.19)

\[ f_p = 20.09 - 142(\theta - 1) + 294(\theta - 1)^2 \] (2.20)

\[ f_s = 590 - 1500(\theta - 1) \] (2.21)

\[ \epsilon_0 = 77.6 + 103.3(\theta - 1) \] (2.22)

\[ \epsilon_1 = 5.48 \] (2.23)

\[ \epsilon_2 = 3.51 \] (2.24)

\[ \theta = \frac{300}{T} \] (2.25)

Where:

(1) \( T \) is the atmospheric temperature in K.

(2) \( L \) is the columnar content of liquid water in kg/m\(^2\).

(3) \( f \) is the signal frequency in GHz.

(4) \( \Theta \) is the elevation angle from the transmit antenna to the satellite; The parameter \( \Theta \) must be in the range from 5° to 90° for the model. This study uses an elevation mask from 5° to 45°.
The final atmospheric attenuation source taken into account is the specific attenuation due to rain, \( \gamma_R \). The specific attenuation due to rain is determined using knowledge of the most recent rain rates in the signal transmitter’s local area, as well as a power-law relationship relating the rain rate to attenuation. Equation (2.26) yields the specific attenuation of the signal due to rain.

\[
\gamma_R = k R^\alpha
\] (2.26)

The parameters of Equation (2.26) include:

\[
k = k_H + k_V + (k_H - k_V) \cos^2(\theta) \cos(2\tau)
\] (2.27)

\[
\alpha = \frac{k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H - k_V \alpha_V) \cos^2(\theta) \cos(2\tau)}{2k}
\] (2.28)

Where:

(1) \( R \) is the rain rate in mm/hr.

(2) \( \theta \) is the path elevation angle from the transmit antenna to the satellite, in degrees.

(3) \( \tau \) is the polarization tilt angle relative to the horizontal, in degrees.

(4) \( k \) and \( \alpha \) constants can be found in Table 1 in Reference [61].

Equation (2.26) yields the specific attenuation of the signal due to rain, in dB/km. Equation (2.29) is used to determine, \( A_{\text{rain}} \), the total attenuation experienced by the signal in dB.

\[
A_{\text{rain}} = \gamma_R r_{\text{atmosphere}}
\] (2.29)

Equation (2.14) is once again used to obtain \( r_{\text{atmosphere}} \), the total distance the signal travels within the atmosphere. Using the distance the signal travels through the atmosphere, instead of the size of rain clouds the signal might travel through, provides a conservative estimate of the attenuation due to rain.
Once all of the atmospheric attenuation effects are calculated, they can be combined using Equation [2.30] to obtain a total atmospheric attenuation in $dB$ experienced by the transmitted signal at each point of the orbit for the system being studied.

$$L_a = A_{dry+water} + A_{cloud+fog} + A_{rain}$$

### 2.3.3 Ionospheric Attenuation

The ionosphere can provide further degradation of a satellite signal. For VHF signals and above, which HDTV signals fall into as a UHF frequency, the absorption of a signal is shown in Equation [2.31].

$$A_{iono} \propto \sec(i) f^2$$

The parameters of Equation [2.31] include:

1. $f$ is the frequency of the transmitted signal, in $Hz$.
2. $i$ is the angle of incidence with the ionosphere, in degrees.

The ionosphere generally absorbs less then 0.1 $dB$ of signal power during a one-way traverse for frequencies greater than 100 $MHz$. Since the HDTV operational band is between 470-890 $MHz$, the ionospheric effects on a signals power received by a satellite on orbit can be assumed to be $< 0.1 dB$ and can therefore be considered negligible for this work.

HDTV signals are generally broadcast with a horizontal polarization. This horizontal polarization will undergo a rotation of its plane due to the effects from the Earth’s magnetic field and the ionosphere. Equation [2.32] calculates the magnitude of these Faraday rotations on the signal as it passes through the ionosphere.

$$\Theta = 2.36e - 14 \frac{B_{av} N_t}{f^2}$$
The parameters of Equation (2.32) include:

1. $\Theta$ is the angle of rotation, in rad.
2. $B_{av}$ is the Earth’s magnetic field strength, in Wb/m$^2$.
3. $f$ is the transmission frequency, in GHz.
4. $N_t$ is the Total Electron Content (TEC) along the slant propagation path, in electrons/m$^2$.

The Faraday rotation of the transmitted signal will undergo a diurnal, seasonal, and solar cyclical behavior, which allows for it to be predicted ahead of time. Table 2.5 summarizes the expected Faraday rotation, assuming a magnetic field strength of 50 $\mu$T, as it relates to TEC and frequency.

Group delay is the time delay in excess of free-space travel time. Equation (2.33), calculates the group delay that a signal will experience due to the ionosphere.

$$t = 1.345 \frac{N_t}{f^2} \times 10^{-7}$$ (2.33)

The parameters of Equation (2.33) include:

1. $t$ is the time delay, in sec.
2. $f$ is the transmission frequency, in Hz.
3. $N_t$ is the integrated TEC along the slant propagation path, with TEC in electrons/m$^2$.

Table 2.5 summarizes the approximate group delay expected for ATSC signals during both peak and quiet ionospheric activity.

The work presented here uses one simple model of ionospheric physics; more sophisticated models would improve the navigation system. Some other ionospheric models available for use include the International Reference Ionosphere, the Parameterized Ionospheric Model, the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model, and the NeQuick Ionosphere model.
Table 2.5: Summary of expected peak delay for an ATSC signal.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>TEC (el/m²)</th>
<th>Faraday Rotation (rad)</th>
<th>Group Delay (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>470</td>
<td>$10^{16}$</td>
<td>$5.342 \times 10^{-2}$</td>
<td>$6.09 \times 10^{-9}$</td>
</tr>
<tr>
<td>470</td>
<td>$10^{18}$</td>
<td>5.342</td>
<td>$6.09 \times 10^{-7}$</td>
</tr>
<tr>
<td>890</td>
<td>$10^{16}$</td>
<td>$1.4897 \times 10^{-2}$</td>
<td>$1.698 \times 10^{-9}$</td>
</tr>
<tr>
<td>890</td>
<td>$10^{18}$</td>
<td>1.4897</td>
<td>$1.698 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Further study of these models are needed to identify the best model for use with an HDNav system.

2.3.4 Antenna Gains

The transmitting antenna gain parameter is calculated by taking the documented horizontal gain pattern of the chosen transmission tower, taken from the Federal Communications Commission (FCC) database and the generic vertical gain pattern used, and recommended by, the FCC when evaluating a transmitting tower’s installation application. The generic vertical gain pattern used by the FCC does not go above $10^\circ$ in elevation angle so the simulation assumes an exponential drop-off in signal strength for elevation angles above this threshold, as recommended in FCC documentation. The HDTV towers have a main broadcast lobe that remains within a few degrees of the horizon, generally going no further than $5^\circ$ above the horizon. By assuming an exponential drop-off in signal strength above this main-lobe, side-lobes are not seen in the simulations. The existence of side-lobes in the true transmission patterns of HDTV towers make the assumptions used in these simulations conservative. The horizontal and vertical gain patterns are combined to yield a full 3D gain pattern for the HDTV transmission source.

Independent signal strength measurements from aircraft flights over the CBS KCNC ATSC transmission tower, located in Golden, CO, indicate that the signal is transmitted at a high-power level up through $55^\circ$ elevation angles for a satellite to take advantage of it for use on orbit. Above the $55^\circ$ elevation angle threshold collected data is very sparse. More information is needed to classify the signal strengths above this level. The raw signal strength measurements can be seen in
For this study, a lower bound of $5^\circ$ is used in order to account for excess atmosphere and local topography interfering with the signal’s transmission. The receiving antenna gain pattern is then calculated using Equation (2.34):

$$R_{gain} = \frac{4\pi A_e}{\lambda^2}$$  \hspace{1cm} (2.34)

where $A_e$ is the effective aperture area of the receiving antenna on the satellite being studied, in $m^2$, and $\lambda$ is the signal’s wavelength, in $m$.

---

### 2.3.5 Link Analysis

The Effective Isotropic Radiated Power (EIRP) can be found using the ERP for a given transmission antenna obtained from the FCC database. Once the ERP is determined, the EIRP can be calculated using Equation (2.35):
\[ EIRP = ERP + 2.15 \text{ dB} \]  

Equation (2.36) is used to calculate the satellite’s received signal power, \( P_{\text{received}} \), in \text{dBW}.

\[ P_{\text{received}} = EIRP + L_s - L_a + R_{\text{gain}} + T_{\text{gain}} \]  

(2.36)

Where \( T_{\text{gain}} \) is the antenna gain of the transmitting antenna in \text{dB}.

The power flux density defines the reduction in power density a signal undergoes between transmission at the HDTV tower and reception at the satellite. Equation (2.37) computes the power flux density, \( PFD_{\text{received}} \), of the system.

\[ PFD_{\text{received}} = \frac{P_{\text{trans}}}{4\pi d^2} \]  

(2.37)

Where \( d \) is the distance between the transmit tower and the satellite in \text{km}.

With all this information collected, the system’s carrier to noise ratio, \( CN_0 \), can be calculated using Equation (2.38).

\[ CN_0 = P_{\text{received}} - 10 \log_{10}(T_{\text{sys}}) + 228.6 - L_{\text{front end}} \]  

(2.38)

The parameters of Equation (2.38) include:

1. \( L_{\text{front end}} \) is the noise and other losses in the receiver front end, in \text{dB}.

2. \( T_{\text{sys}} \) is the receiving antenna system noise temperature in \text{K}.

2.4 Signal Strength Analysis

2.4.1 Low-Earth Orbit

The orbit used for the LEO study is an ISS orbit propagated for one day using two-body dynamics. The HDTV tower used is located in Portland, Oregon at a location of 45.516° N, 237.2672° E, and 0.6134 km above sea-level. Information from the FCC’s TV Query database
shows the transmitting antenna transmits at a frequency of 536.31 MHz with an omni-azimuthal antenna. The atmospheric attenuation model uses the atmospheric conditions in Portland from March 1st, 2015. The model is also assuming the receiving antenna on the satellite is an omni-directional antenna. Finally, the simulation assumes the receiving antenna has a system noise temperature of 290 K, the same as a GPS Block IIA satellite, along with losses in the front-end equaling 4.5 dB. The link connection between the satellite and transmitting tower is calculated over a one-day period, and the results can be seen in Figure 2.15.

Figure 2.15: Link budget for LEO satellite using HDTV signal transmitted from a tower in Portland, OR. A 0-45° elevation mask is used for this calculation, with the red representing a 0-5° elevation mask and the blue a 5-45° elevation mask.

The first plot in Figure 2.15 shows the received signal power, in dBW, that the satellite’s receiving antenna will see on orbit; the second plot shows the received power flux density, in dBW/m², a satellite will see; the final plot shows the CN₀, in dB – Hz, that the satellite will see.
on board during the viewing pass.

The main lobe of an HDTV transmission is mainly horizontal. As a result, the transmission gain pattern has the largest effect on signal strength when a satellite is low in its pass. Due to the high signal strength of HDTV transmissions near the horizon, the red segments in Figure 2.15 that correspond to low elevation angles, turn upward. Once the satellite leaves the main lobe of the HDTV transmission, free-space path loss between the satellite and transmission tower is the primary driver of the signal strength as a function of increasing distance. This is represented in the blue segments in Figure 2.15 where the signal strength gradually increases during the ascent portion of a pass. Similarly, after leaving the main transmission lobe the signal strength falls off as the satellite descends, until the satellite re-enters the main transmission lobe.

The satellite passes over the HDTV tower location seven times during the course of a day when in an ISS orbit. For this simulation, the received power of the signal peaks at -90 dBW with an average maximum received power of -92 dBW over the course of a day. The CN0 peaks at 109 dB−Hz during an individual pass and has an average maximum peak at approximately 108 dB − Hz for every pass.

2.4.2 Lunar L1 Orbit

The next orbital regime for the link budget study is a lunar L1 halo orbit. Figure 2.16 show the link connection between the Portland transmission tower and the satellite. The same 5-45° elevation mask is used for this orbit. The signal strength follows the pattern of the range between the transmission tower and the satellite, except for at the beginning and end of a pass. The received signal power follows a steady increase at the end of a pass and a steady decline at the beginning of a pass, which can be attributed to the fact that for a majority of a pass, the satellite is outside the main lobe of the transmitted signal. When outside the main lobe of the transmitted signal, the free-space path-loss is the primary contributor to the signal’s power loss. At the beginning and end of a pass, the satellite is traveling within the main lobe of the transmission, making the transmission tower’s beam pattern the primary contributor to the signals change in strength. For
this orbit and transmission tower combination, the satellite has a maximum elevation angle to the
tower of 55°.

![Graphs](image)

Figure 2.16: Link budget for a lunar L1 satellite using HDTV signal transmitted from a tower in
Portland, OR. A 5-45° elevation mask is used for this calculation.

The satellite passes over the HDTV tower location twice during the course of a day. In this
simulation, the received power of the signal peaks at -143.7 dBW with and average maximum
received power of -145 dBW over the course of a day. The CN0 peaks at 55.6 dB – Hz during an
individual pass, and the CN0 has an average maximum peak at approximately 54.5 dB – Hz.

The noise floor for a signal at the moon is approximately -136.20 dB with no signal processing
gain added. With a maximum received power of -145 dB, using an isotropic antenna, reception
of an HDTV signal is possible out to a cis-lunar orbit when a higher gain antenna is used. Also,
a match filter can be used with the synchronization codes found within the signal to add a signal
processing gain to the received signal strength. These signal processing techniques and gains will
be studied in greater detail in Chapter 4.

2.5 Conclusions

The coverage analysis performed shows the expected coverage that can be provided by HDNav for a satellite in LEO, a Molniya orbit, or a lunar L₁ orbit. The coverage study demonstrates that using 33 towers located only in North America and South Korea, a satellite will be in view of the HDTV signal for at least 15.73% of its orbit if the satellite is in an ISS orbit and as much as 28.73% for the best case LEO. For a Molniya orbit, coverage of 90.44% can be expected using ATSC signal. When towers from around the world, including Europe, Asia, South America, and Australia are included, the coverage for LEO satellites increases to a maximum of 88.70% while the coverage for Molniya orbits increases to a maximum of 99.75%. A lunar L₁ orbit can expect at least 88.18% coverage from ATSC signals and continuous coverage for signals following any of the ATSC, DVB-T, and ISDB-T standards.

The link budget calculations performed show that HDTV signals are a potential source of navigation information for satellites on orbit. Even out in lunar libration orbits, the satellites can expect to be within view of HDTV signals at signal strengths better than those of GPS receivers on the surface of the Earth; and these signals contain synchronization codes similar to the Gold codes used in the GPS signals.

The work presented indicates that HDTV signals are a promising potential navigation data source for use on orbit. HDTV signals are prevalent, highly structured, and high-powered. This chapter demonstrates that their coverage and signal strength are substantial. The combination of coverage and signal strength supports HDNav as a convincing alternative, back-up or replacement system for current navigation methods.
Chapter 3

HDTV Implementation and Operations

HDTV signals are highly structured signals broadcast from dedicated facilities around the world. The facilities that are used to generate and broadcast the signals require specialized equipment. The equipment must have redundancy to continue broadcasting HDTV signals in the event of equipment failure, power outages, or other problems. The local CBS affiliate in Denver, KCNC, built a new transmission facility, which opened in May 2008, to help modernize and refine their signal transmission and streamline their processes. The facility is a state of the art system designed with significant redundancies that minimize chances of a single point of failure preventing the system from operating properly. A site visit to the KCNC facility provided a better understanding of the generation, structure, and broadcast strength of the ATSC signal and tower. The set-up of the facility and the systems used to generate and broadcast a final signal for KCNC are outlined in this chapter.

3.1 Signal Formation

In order to generate the necessary signal, KCNC must receive a feed of the shows to be broadcast from the station in Denver. KCNC does not currently have a fiber optic line connected to their building due to the high cost of running fiber optics to the facility located on the top of Lookout Mountain in Golden, CO, but the company is performing a feasibility study on the issue. Currently, the transmission facility receives the feed from a Denver station via microwave antennae located on the eastward face of the facility. Figure 3.1 shows some of these receivers found at the
At the transmission facility, the feed from the Denver station must be modulated onto the proper frequency and amplified to the proper transmission power. KCNC in Denver operates on the 599 MHz frequency band and broadcasts at 1 MW of ERP. To begin the signal formation, the feed is passed to one of the Harris APEX Ranger class CZ1000 exciters in the facility. Each exciter is locked to GPS but also has a local oscillator back-up. The APEX exciters, when locked to GPS, operate at 0.83 ppb. If the GPS signal is lost, the exciters operate at 0.334 ppm, using only the backup oscillator. Figure 3.2 shows the exciter and other initial signal generation equipment used at the source of the signal generation process.

For all towers using a GPS disciplined oscillator the GPS clock corrections will need to be sent to the satellite using autonomous HDNav in order to properly correct for clock drift. If the GPS signal is lost the backup oscillators at the transmitting tower will need to be monitored with clock corrections sent up to the satellite in order for navigation to maintain accuracy. The backup oscillators at CBS are specified at 0.334 ppm which is a daily accuracy of 0.0288 sec at the time of initialization, over time this performance degrades and monitoring stations of the transmission towers would need to be established in order to properly track the clock drift in the HDNav system, since these systems do not currently exist.

Once the signal has been initiated, it is sent through a series of amplifiers, filters, and wave-
guides in order to shape, polarize, and power the signal to the proper levels for broadcast. Figures 3.3 and 3.4 show several of the waveguide sections and filters the signal must pass through in order to be completely and properly built into the final signal.

After the signal has been amplified and formed, a large mass filter completes the signal shape. The mass filter cuts approximately 65 $dB$ of power off the sides of the signal to obtain a proper roll-up/-off from the noise floor to the signal. The facility is equipped to use circular
Figure 3.4: Sections of filter banks used to shape the signal.

polarization, should KCNC decide to transition from horizontal polarization. In order to transfer from a horizontal polarization to a circular polarization scheme, the waveguides would need to be connected to an existing set of unused waveguides seen in Figure 3.5.

Figure 3.5: Waveguide that would be used to transform the signal into a circular polarization scheme.
While the signal is being generated, a set of switches allows operators to alter the signal’s path through the facility, and change which antenna transmits the signal. These switches, seen in Figure 3.6, allow engineers to test and/or use the auxiliary transmission towers. They also help facilitate the testing of various backup components in the signal generation chain. The system is usually set to its normal operation procedures, and the switches are used to change the signal path only as necessary, or as testing is required.

![Switches used to alter the signals path through the system.](image)

Figure 3.6: Switches used to alter the signals path through the system.

3.2 Broadcasting the Signal

Once the signal is complete, it runs through waveguides within a sloped 75 m tunnel (seen in Figure 3.7) that connects the facility to the broadcast tower. An analysis determined it would be more effective to use tunnels instead of an overground system with ice shields to protect the signal from potential ice problems in Colorado’s winters. Due to the high power levels of the signal, each waveguide within the tunnel carries only one half of the signal. This prevents the signal from destroying the waveguides due to potential hot-spot formation and subsequent vaporization of the copper waveguide.
When the signal is sent to the broadcast tower, the two halves of the signal are combined and pushed to the transmitting antenna. Figure 3.8 shows the transmitting antenna used at the KCNC facility. This is a Diellectric TUA-C3-12/36U-1-S antenna that has a $< 1^\circ$ downward mechanical beam-tilt in order to help direct the signal to the target audiences. The antenna broadcasts the signal at a constant ERP of 1 MW toward the east, since the mountains behind the antenna block the signal to the west. The transmission antenna location is measured to better than 2 ft precision in order to meet FCC requirements.

3.3 System Back-ups

If the power is interrupted to the KCNC facility, or if other failures occur, numerous systems are in place to help ensure no interruption in the broadcast occurs. The first of these back-ups is a set of three mechanical flywheels and two different uninterrupted power supply (UPS) systems. The flywheel housings and both UPS systems can be seen in Figure 3.9.

When the UPS is being used, the engineers at the facility turn on the backup generators. For backup generators, KCNC uses two 1.5 MW diesel generators, each of which use 50 gallons of
fuel per hour to run. Figure 3.10 shows one of these generators. In order to maintain a continuous broadcast presence, KCNC can run these generators continuously for approximately two weeks before running out of fuel on-site at the facility.

In addition to the backup power systems, the KCNC facility has a secondary set of signal exciters. Each signal generation block is connected to two Harris APEX exciters connected to them for redundancy. There is also a backup initial signal-generation equipment set that has its own two exciters. The backup equipment uses a digital system to help generate the signal and can be seen in Figure 3.11.
The KCNC facility has backup waveguides to complete the redundancy of the system. These backup waveguides allow the signal to be moved if maintenance needs to be performed on any section of the system components or if an unexpected hot-spot forms and destroys equipment. The operators use these waveguides every few weeks to check that they are working and fully functional.

This backup equipment exhibits the system redundancy implemented to help prevent customers from unexpectedly losing the signal and therefore losing KCNC and CBS money. Overall, these backup systems allow for a precise, continuous signal to be generated and broadcast. With the back-up system used in the facility, there is no known single-point of failure in the system.
3.4 Conclusions

The KCNC site main systems and backup systems continuously generate and broadcast an HDTV signal. This signal follows all FCC and ATSC regulations and provides customers with the necessary final signal. The specialized equipment is tested and maintained by the on-site operators. All of these components come together to provide a continuous presence for CBS in the Denver region. This continuous presence is seen by HDTV providers around the world, as well. By having a strong and continuous presence around the world, HDTV providers maintain a network of potential navigation data for satellites.
Chapter 4

Signal Processing of HDTV Transmissions for Satellite Navigation

High Definition Television (HDTV) transmission towers around the world broadcast signals at very high power levels - many over 1 MW of effective radiated power (ERP) in Australia, Europe, and the US. These power levels make HDTV signals very promising navigation beacons for satellites in orbit. However, high power levels alone are not enough to make these signals promising, or even effective, navigation beacons. Signals must also contain features that an on-board computer can both detect and extract from the signal in order to generate navigation observables for navigation filters to use. HDTV signals contain both the necessary signal qualities and high broadcast ERP from the transmission towers to be viable for use as a source of navigation observables. This chapter studies the ATSC transmission standard, and describes the various digital signal processing (DSP) techniques and methods needed to extract timing from the received signals. The signal structure, reception, processing, and timing information that can be extracted from the signal are studied to examine the feasibility of HDTV signals in real-world applications. The processing power required by a CPU to perform these operations is also evaluated, as this is a potential limitation in the implementation of these signals as navigation beacons.

4.1 Description of HDTV signals

As detailed in Chapter 2, there are several different encoding schemes used throughout the world for HDTV broadcasting including ATSC, DVB-T, ISDB-T, and DTMB. While the DVB-T and ISDB-T standards also contain useful structure components for extracting navigation informa-
tion, this paper will focus on the use of ATSC signals found in North America and South Korea. The
use of other standards for obtaining navigation information, including the orthogonal frequency-
division multiplexing (OFDM) modulation schemes used by the DVB-T and ISDB-T standards, is
a topic of future work.

4.1.1 ATSC Signals

This section provides a background about the structure and synchronicity of the ATSC
standard. All ATSC signals are transmitted using the same guidelines to regulate the signal and
ATSC Digital Television Standard Part 2: RF/Transmission System Characteristics defines these
standards. As per these guidelines, all ATSC HDTV signals are transmitted using a 27 MHz
clock that is then used to generate a symbol rate of \( f_s = 10.762237 \text{ MHz} \). The ATSC frame is divided
into two data fields, each of which is comprised of 313 data segments, which are 832 symbols. Each
frame also contains a field synchronization segment at the beginning of the data field. The ATSC
frame and data field structures are described in Table 4.1 and can be seen in Figure 4.1.

<table>
<thead>
<tr>
<th>Structure</th>
<th># of Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>3 (bits)</td>
</tr>
<tr>
<td>Data Segment</td>
<td>832</td>
</tr>
<tr>
<td>Data Field</td>
<td>260,416</td>
</tr>
<tr>
<td>Frame</td>
<td>520,832</td>
</tr>
</tbody>
</table>

The ATSC standard uses amplitude shift key (ASK) and 8-ary vestigial sideband modulation
(VSB) which has symbols of three bits of data encoded onto it. The first segment of each data field is
the field synchronization segment, defined by the ATSC Standard for Transmitter Synchronization
as follows:

Data Field Synchronization segment (FSS) is inserted by the modulator. The FSS carries several pseudo-random binary sequences (PRBS) used as training signals for adaptive equalizers in receivers. One of those PRBS sequences alternates in phase from FSS-to-FSS. This creates a Data Frame structure composed of two
Figure 4.1: Structure of the ATSC signal.

Data Fields. Because of the integer phase relationship between the Data Frame and its two Data Fields, it is possible to synchronize the Data Frame structure and derive the Data Fields from the Data Frame structure.

The FSS is the component of the signal used to lock on and track the signal as it is being received. The FSS only occur twice in every frame, with data segment synchronization sections (DSS) appearing in every data segment in a frame. The DSS is a 4-symbol, segment synchronization piece composed of a [-1, 1, 1, -1] symbol structure. This segment synchronization section at the beginning of each data segment does not carry any frame data but could be detected and used in a feature detector or as a counter between FSS.

The segment synchronization section occurs at the beginning of every data segment. The frames, containing the data segments, repeat every 77.3 µs. This makes the frame rate for these signals 20.6655 frames/sec; therefore, each frame in an ATSC signal is approximately 14,507 km long. Since a receiver will pick up 20.6655 frames/sec, there will be 41.34 FSSs every second. This provides frequent opportunities for the system to lock on the signal and allows for both a short acquisition time and strong lock.
4.1.1.1 Signal Timing Requirements

In order to generate the signals described above, there must be a strong timing standard for the oscillators that create the signals. These timing standards are described fully in Sections 4.3 and 12.1 of the ATSC Standard for Transmitter Synchronization and will be outlined here.

The ATSC standard recognizes how important timing is in achieving transmitter synchronization and signal generation. Specifically, the ATSC standard uses timing standards in two different aspects of signal synchronization: “establishing phase relationships between data frames emitted by multiple transmitters and establishing phase relationships between data frames emitted by single or multiple transmitters and an external time reference.” The ATSC standard defines the period of the Transport Stream bit rate, 19.39 Mb/s, as the fundamental unit of time expression in all ATSC signals, in order to specify what the timing standards need to achieve synchronization. This leads to an ATSC defined time unit of 51.57 ns. From this time unit, the ATSC standard requires that all transmitters have a 50 ns or better accuracy every second.

The ATSC standard results in a design where all transmitters in a region broadcast their frames at the same time. This requirement was written into the standard to provide the following benefits:

1. Improved channel change time between services on different frequencies in the same region.
2. Minimized disturbance during hand-off of services from a single service provider from one region to the next.
3. The opportunity to use ATSC mobile/pedestrian/hand-held broadcasts for geo-location by receiving devices.

In order to achieve the desired timing for these signals, the transmitters require an external reference source to synchronize the oscillators. The standard defines the external reference as the GPS clocks: “The external time reference shall be the one provided by the Global Positioning System (GPS) satellite navigation system and shall be determined with an accuracy of 50 ns or
better at all network locations. The transmitter system will continuously steer the phase of the local oscillator to maintain 1 pulse per second (pps) with GPS time. Overall, the timing requirements make the ATSC signal a potential navigation signal source.

### 4.1.1.2 ATSC Signal Features

When collecting and processing ATSC data, there are several signal components to look for to ensure the data is clean and the signal is strong. For ATSC signals, the constellation should be a square that rotates in time. An example of an QAM-64 constellation is seen in Figure 4.2. The constellation shows both an ideal signal and a signal with noise.

Figure 4.2: ATSC in-phase and quadrature constellation.

An ATSC signal has a 6 MHz bandwidth with sharp ramp up and down at either end. An example of a fast Fourier transform (FFT) of an ATSC signal is shown in Figure 4.3. The FFT provides several useful pieces of information, including the signal-to-noise ratio (SNR) of the received signal as well as the location and strength of the signal's pilot tone. The ATSC pilot tone has a 2 mHz resolution per FCC requirement 73.622 and is generated 10 dB above the rest of the signal.
After determining the data is clean and if the rest of the signal looks appropriate, the PRBS code autocorrelations can be performed. The ATSC signal contains both FSS and DSS synchronization segments that can be used for autocorrelation. The examination presented here acquires timing information by performing an autocorrelation on the FSS.

The FSS is comprised of eight different sections. The first piece of the FSS is the four-symbol DSS code. Following the DSS is a 511-symbol pseudo-random sequence (PN511), which is defined by Equation 4.1 and is pre-loaded with a starting setup of 010000000.

\[ X^9 + X^7 + X^6 + X^4 + X^3 + X + 1 \]  

(4.1)

Following the PN511 code, the FSS has three segments of a 63-symbol pseudo-random sequence (PN63), with the middle PN63 sequence inverted on every other FSS. The PN63 code is defined by Equation 4.2 and is pre-loaded with a starting setup of 100111.

\[ X^6 + X + 1 \]  

(4.2)

The next set of components of the FSS is the VSB mode bits. These segments are comprised of 24
symbols and shall “signal the VSB mode for the data in the associated Data Field. The values of
these symbols shall be determined by the values of the VSB mode bits as defined in Table 5.3.”
The following 92 symbols found in the FSS are reserved for use when enhanced data transmission
methods are used. Finally, because the ATSC signal uses a cyclic prefix, the final 12 symbols of the
segment shall correspond to the last 12 symbols of the previous segment. For every section in the
FSS, a binary value of 0 corresponds to a symbol of level -5 and a binary value of 1 corresponds to
a symbol of level +5.

4.2 GNU Radio Overview

The GNU Radio program facilitates the generation of simulated ATSC signals for study as
well as control of the software defined radios (SDRs) used to collect real data. GNU Radio is
an open-source radio processing toolkit that allows the user to control radio peripherals, perform
signal processing, and provide signal simulation capabilities. The library is supported by a large
community of developers that produce new processing modules. Designs in GNU Radio can be
produced by building block diagram flow graphs that compile down to Python executable files.

In addition to supporting numerous, common signal processing modules, GNU Radio also
includes support for interfacing with different physical radio peripherals. These interface modules
handle the configuration of the radio device and the flow of in-phase and quadrature (IQ) data
between the processing software and radio.

GNU Radio designs can be developed to perform a variety of processes and are very useful
in developing GUIs to visualize the processing of radio data and applications to record IQ data
for post processing or visualization. In addition to interfacing with data generated by a radio
peripheral, GNU Radio also supports the generation of simulated IQ data that can be used to test
and verify signal processing algorithms. In this work, GNU Radio was used extensively to simulate
ATSC signals, visualize the processing of ATSC data, and record raw IQ data that was used to
develop the field programmable gate array (FPGA) firmware. Figure 4.4 shows an example data
acquisition flow graph, and Figure 4.5 shows the visualization of the ATSC spectrum using the
GPU accelerated gr-fosphor block in GNU Radio.

Figure 4.4: GNU Radio flow graph design for data acquisition. The source of the data is the radio peripheral and the sink is a pair of binary files.

Figure 4.5: Waterfall plot of ATSC Spectrum generated using gr-phosphor in GNU Radio. Data is centered at 527 MHz with a 10 MHz span. The characteristic pilot tone is readily observed between 524 and 525 MHz.
4.3 Results using Simulated Data

GNU Radio is used to create an ATSC signal simulation suite for testing signal processing algorithms. Figure 4.6 shows the signal generation and visualization flow graph used for this work. This setup was then used to generate ATSC IQ data used to verify signal structure components and signal detection techniques. After data was collected from the GNU Radio simulator, autocorrelation tests were performed on the signal using the known FSS PRBS codes found in the *ATSC Digital Television Standard - Part 2:RF/Transmission System Characteristics*.

Figure 4.7 shows the results of this convolution, and Table 4.2 summarizes the peak detections and the timing that these peaks provide. The results from the simulated data show the expected timing between peaks and a high SNR from the autocorrelation. The exact same timing between peaks is expected for a simulated signal without any Gaussian white noise or signal delays added to it. The spacing between peaks is expected to have minor deviations in peak time when real data is collected due to noise and delays in the signal. Processing simulated signal data confirmed what was expected from the signal given the signal structure and timing requirements.

![GNU Radio flow graph design for simulating ATSC signals.](image)

Figure 4.6: GNU Radio flow graph design for simulating ATSC signals.
Figure 4.7: FSS autocorrelation using simulated data.

Table 4.2: Simulated ATSC signal autocorrelation results.

<table>
<thead>
<tr>
<th>Peak Detection</th>
<th>Peak Value (dB)</th>
<th>Time Since Last Peak (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37.5165</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>38.8123</td>
<td>24.19719</td>
</tr>
<tr>
<td>3</td>
<td>37.5183</td>
<td>24.19719</td>
</tr>
<tr>
<td>4</td>
<td>38.8455</td>
<td>24.19719</td>
</tr>
<tr>
<td>5</td>
<td>37.4977</td>
<td>24.19719</td>
</tr>
<tr>
<td>6</td>
<td>38.8652</td>
<td>24.19719</td>
</tr>
<tr>
<td>7</td>
<td>37.5253</td>
<td>24.19719</td>
</tr>
<tr>
<td>8</td>
<td>38.8444</td>
<td>24.19719</td>
</tr>
<tr>
<td>9</td>
<td>37.5111</td>
<td>24.19719</td>
</tr>
</tbody>
</table>

4.4 SDR Processing Overview

There are several choices for methods to process the ATSC signal, including both CPUs and FPGAs. The processing requirements for a SDR can be very demanding. The bandwidth of
unprocessed IQ data can range from 2.0 MB/s for 8-bit samples at 1 MSPS up to 200 MB/s for 16-bit samples at 50 MSPS. Most modern computer peripheral interfaces, circa 2016, could easily handle the low end of that range, but the higher end of that range would require higher bandwidth interfaces, such as USB 3.0, PCIe, or 10 GigE. This also has ramifications on the type of non-volatile storage used if the application requires uninterrupted data recording.

In addition to the challenges presented with interfacing, there are challenges associated with processing such a high data rate. Radio data is generated in a continuous stream. This presents a challenge to CPU- or GPU-based processors, as these devices process data in packets. To keep up with the high rate-streaming data, the CPU must break the stream into smaller chunks and process each section fast enough so that the CPU does not drop any of the data.

CPUs are useful because they are extremely flexible, and many tools and software libraries exist to accelerate development times; however, they require a lot of processing power to manage the data in a stream. As an alternative, FPGAs can be used to lower the CPU data-rate requirements by pre-processing the data. FPGAs can be designed to process data in a stream, allowing even low-cost chips to significantly reduce the data bandwidth presented to a CPU. Although FPGAs have better processing capabilities in this situation as compared with CPUs, they tend to have fixed performance with a limited number of tools and firmware libraries to use in development. Moreover, FPGAs require designers to use hardware description languages that physically describe the connections and configurations of logic circuits. Designers must also be cognizant of the limited resources available on the FPGA and design their circuits to meet timing requirements. The payoff is a massive reduction in data rate. The solution used for this work, described in Section 4.7, leverages the processing strengths of FPGAs combined with the flexibility of CPUs.

4.5 SDR Hardware

For this work, several different SDR hardware systems were used. These included different radio peripherals, as well as different processing systems.
4.5.1 Radio Peripherals: HackRF

The HackRF One from Great Scott Gadgets was used extensively to capture data for post-processing. This device can tune from 1 MHz to 6 GHz, outputs 8-bit samples, and can sample up to 20 MSPS. The radio data is formatted internally using a complex programmable logic device (CPLD) and passed to a processor over USB 2.0.\[76\]

4.5.2 Radio Peripherals: AD9361

The AD9361 is a radio-frequency-integrated-circuit (RFIC) produced by Analog Devices. The radio conversion chains and digitizers are all fully integrated into a single chip. This allows the device to be small, light, and draw little power, making it an ideal candidate for embedded systems or applications constrained by size, weight, and/or power. This radio can tune from 70 MHz to 6 GHz, outputs 12-bit samples, and supports up to 56 MHz of instantaneous bandwidth on two full duplex channels.\[76\] For this work, the FMCOMMS3 board was used to break out the functionality of this radio peripheral.

4.5.3 Processors: Laptops

Modern laptops tend to have both the CPU power and support for the high-rate interfaces required to run high-bandwidth radio processing. Moreover, they tend to have easy access to all the software libraries and repositories required to run the latest versions of GNU Radio. Much of the data acquisition and processing for this body of work was performed using laptops for their ease of use. Their primary drawback is their size and cost.

4.5.4 Processors: Single Board Computers

The SolidRun HummingBoard has been used for this work and is shown in Figure 4.8. This single board computer (SBC) features a 1 GHz quad core CPU with 1 GB of RAM and it supports USB 2.0, PCIe 2.0, and SATA II.\[74\] The capable CPU and support for high-bandwidth interfaces makes the SBC a strong candidate for wide-band data acquisition. When coupled to the HackRF
and a 128 GB mSATA solid state hard drive, the HummingBoard can record up to 57 minutes of IQ data sampled at 20 \textit{MSPS}.

Figure 4.8: SolidRun Hummingboard SBC.

4.5.5 Processors: Zedboard

The final processor used in this body of work was the Zedboard; a development board based on the Xilinx Zynq processor. The Zynq is unique in that it incorporates a dual core Advanced RISC Machines (ARM) CPU and FPGA fabric on the same chip. The CPU and FPGA fabric are connected via an AXI based data bus. The Zynq features Advanced eXtensible Interface (AXI) high performance (HP) connections, as well as AXI general purpose (GP) connections. The AXI HP connection supports wide-bandwidth transfers and would typically be used for moving unprocessed IQ data. The AXI GP connection is much slower and is used for setting or reading registers. The ARM CPU runs at 667 \textit{MHz} by default but can support rates up to 1 \textit{GHz}. The Zedboard supports USB 2.0 and gigabit Ethernet but uses MicroSD cards for non-volatile storage which limits its ability to store IQ data. For this work, the Zedboard is coupled with the FMCOMMS3 card over an FPGA mezzanine card (FMC) connector. The Zedboard and FMCOMMS3 card is pictured in Figure 4.9.
4.6 Results using Real Data and Post Processing

Using an omni-directional antenna, the HackRF SDR and the GNU Radio flow diagram seen in Figure 4.4 ATSC IQ data was collected from the KCNC Denver transmission tower centered at 599 MHz. This data was then post-processed using the same techniques as the simulated ATSC signal data. The autocorrelation results can be seen in Figure 4.10 and are summarized in Table 4.3. The autocorrelation peaks detected using the real data have a similar SNR to the simulated signal results, but average an absolute peak height approximately 10 dB lower. The high SNR found in the data allow for peak detections to still occur autonomously. The noise floor of the collected data is not as consistent as the simulated signal results, which is to be expected given the noise that is introduced into the system when the signal is generated, transmitted, propagated through the air, and received. Even with this floor shifting over time with the signal, the SNR of the autocorrelation peaks remain consistent and moves with the noise floor.

The timing between autocorrelation peaks in the collected data is not exactly the same between every peak. There is a 71.43 ns variation between the largest and smallest peak separation in the processed data. This can be explained by system noise, signal noise, sampling frequency, and atmospheric delay of the signal while it travels. The discrete nature of the data also indicates that the system is seeing a $+/−1$ clock cycle variability in the sample returns. This is explained...
by using a 6 MHz clock in the SDR with a signal that has a 6 MHz bandwidth but is being compressed. This causes the peak to show up spread across two clock gates with the power in one gate being higher than the other, which leads to the +/- one clock cycle return. The system as it is designed could meet timing up to 150 MHz and potentially up to 300 MHz with minor tweaks.

![Autocorrelation of FSS and collected data](image)

Figure 4.10: FSS autocorrelation using collected data.

### 4.7 FPGA Firmware Design

The core digital signal processing (DSP) modules of the automatic ATSC detection firmware were coded in VHSIC hardware description language (VHDL). The design was broken down into its component DSP functions. Each function was developed into separate VHDL modules to maximize the design’s re-usability, portability, and modularity. Each module is highly parameterized and reconfigurable. The DSP firmware is connected to the radio peripheral using firmware provided by Analog Devices. The configuration and control of the firmware is handled over the AXI GP connection. The results of the detection were also communicated over the the AXI GP connection.
Table 4.3: Collected ATSC signal autocorrelation results.

<table>
<thead>
<tr>
<th>Peak Detection</th>
<th>Peak Value (dB)</th>
<th>Time Since Last Peak (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.0536</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>25.2878</td>
<td>24.19714</td>
</tr>
<tr>
<td>3</td>
<td>25.4499</td>
<td>24.19707</td>
</tr>
<tr>
<td>4</td>
<td>28.1565</td>
<td>24.19707</td>
</tr>
<tr>
<td>5</td>
<td>28.0154</td>
<td>24.19714</td>
</tr>
<tr>
<td>6</td>
<td>29.4666</td>
<td>24.19707</td>
</tr>
<tr>
<td>7</td>
<td>26.7260</td>
<td>24.19714</td>
</tr>
<tr>
<td>8</td>
<td>26.7583</td>
<td>24.19707</td>
</tr>
<tr>
<td>9</td>
<td>24.0126</td>
<td>24.19714</td>
</tr>
<tr>
<td>10</td>
<td>27.4201</td>
<td>24.19707</td>
</tr>
<tr>
<td>11</td>
<td>27.6656</td>
<td>24.19707</td>
</tr>
</tbody>
</table>

4.7.1 DSP Design

The DSP firmware is composed of two major building blocks: the complex autocorrelator and the moving average detector. The autocorrelator takes in the IQ data and applies the complex ATSC frame-sync sequence. The output of the autocorrelation is converted to magnitude squared and passed to the detector. The detector calculates a moving average of the magnitude-squared output and scales this to set a detection level. Finite state machine logic is used to flag a detection and save its associated time and power.

4.7.2 DSP Design: Autocorrelator

The autocorrelator is designed based on previous work out of the University of Colorado - Boulder Cyber Physical Systems Lab. This design uses the sign of the data and correlation sequence to approximate an autocorrelation. By using just the sign bits, the autocorrelator does not require any multipliers to run. The drawback is that the correlation sequence needs to be well approximated by its sign alone. The ATSC sequence meets this criterion since it is based on Gold codes. A comparison of full, complex multiplier autocorrelation and sign-based autocorrelation
for the ATSC sequence is shown in Figure 4.11.

Figure 4.11: Autocorrelation results calculated in post processing. Data recorded over the air at 6 MSPS. Red shows sign-only results while blue is the full complex multiplication results. Both show similar signal to noise ratio.

The autocorrelator is parameterized to take in generic data widths, and can be compiled for sequences of lengths equal to a power of two. New filter coefficients are loaded simply by playing in data and a data valid signal for \( n \) clock cycles, where \( n \) is the length of the sequence. For this design, the ATSC frame sync-sequence was found to last for 464 clock cycles (at 6 MSPS). An autocorrelator of length 512 was designed and the frame sync was padded with zeros to fill out the extra length. As a complex autocorrelation is being performed, four filters are instantiated, one for each combination of I and Q. The resulting I and Q output is calculated by summing the appropriate filter outputs. The complex output of the autocorrelators is then converted to magnitude squared by squaring the I value and the Q value and summing the results.

4.7.3 DSP Design: Moving Average Detector

The detector is based on a moving average filter, which calculates a running approximation for the mean of the autocorrelation output and is then scaled with a multiplication to set a detection
level. This detection scheme is similar to a constant false alarm rate (CFAR) detector as it is calculating a running level to detect on. In contrast to a true CFAR detector, no guard cells are used in this implementation. The moving average filter is built using a block RAM (BRAM) module to minimize logic gate usage. The core is constrained to compiling for power-of-two length moving averages. This is done to maximize the efficiency of the BRAM utilization, minimize the complexity of memory addressing, and allow a logical right shift to be used to normalize the accumulation term. The core has been parameterized to take in arbitrary data widths and power-of-two window sizes. The output of this filter is scaled by a multiplier and fed into a detection finite-state-machine (FSM). This FSM compares the autocorrelator outputs and detection levels looking for peaks. The FSM is designed to mitigate multiple triggers by ignoring successive detections for a period of time after the first peak is observed. When a new detection is found, the FSM logic latches the current FPGA time (implemented using a simple, 32-bit counter running at 6 MSPS) and the maximum magnitude-squared power value observed in the most recent detection period. That maximum value is reset for the next period and once the user specified hold-off time has been met, the FSM allows for new detections.

4.7.4 Supporting Firmware Design

The detector settings and autocorrelator coefficients are configured using the AXI GP bus. This bus runs at 100 MHz with bursty transmissions. As the design runs at 6 MSPS, clock domain crossing firmware was developed to bridge the gap for register-level access. This firmware clocks new values through a series of registers on the input clock side and a series of registers on the output clock side. As the autocorrelators contain 512 coefficients, a dual port BRAM and FSM control were implemented to handle their configuration. The user loads the BRAM on the AXI clock domain. When the BRAM is fully loaded, the FSM reads the data out of the other port clocked on the DSP clock domain.

When a new detection is made, the DSP firmware writes a flag register on the AXI bus along with the time and power information associated with the detection. These also go through
clock-crossing firmware to mitigate meta-stability or race conditions.

### 4.7.5 Software Design

The Zynq's ARM runs a Linux-based operating system. Currently it runs the Linaro distribution provided by Analog Devices with their FMCOMMS3 card. The radio configuration is currently handled manually using the provided AD9361 driver developed by Analog Devices. This driver uses the industrial I/O (IIO) device drivers to interface with the radio. The AXI GP ports are interfaced to the operating system using the generic user-space I/O (UIO) driver. This driver presents device files with which the user interacts. Currently, a C program is used to memory map the UIO devices and interact with them to configure the firmware settings and take data. The configuration happens first in a serial manner. To take data back from the FPGA, the software continuously polls the detection flag register. When the flag goes high, the software reads the associated power and time registers, then writes a zero to the flag register to clear it. New data is appended to an array and eventually written to a binary file for post processing.

### 4.7.6 FPGA Detection Results

Currently, the firmware is designed to clock at 6 MSPS. This is the minimum bandwidth required for the ATSC sequence. It gives a timing resolution of 167 ns. As the DSP modules were designed to be modular, the design could be quickly re-compiled to over-clock at 12 or 24 MSPS, which would improve the timing resolution at the cost of higher resource draw. Currently, the design uses approximately 9% of the available logic gates, one multiplier, and one BRAM. The resource draw is shown in Figure 4.12.

Data was taken over the air in the Cyber-Physical Systems Lab at CU Boulder using the Zedboard. A joint test action group (JTAG) debugger was used to capture internal debug data. Figure 4.13 shows an autocorrelation output and associated detection level observed when tuned to 617 MHz.

Multiple detections were examined at 617 MHz using a variety of scaling values for the moving
Figure 4.12: FPGA resource utilization table for Zedboard Zynq. Only one multiplier is used, but three are instantiated. Two were implemented in gates by the design tools for this run.

Figure 4.13: FPGA autocorrelator and moving average detector output. A correlation peak is observed.

The moving average level was scaled by a factor of 15 for these detections. Many detections were observed near the expected value of 24.2 ms. False detections were also observed. Additionally, detections were observed at 2x and 3x the expected value. These can be attributed to missing a detection in the pulse train, but observing the subsequent detection.
Figure 4.14: Peak spacing detections in milliseconds plotted as a function of detection number. The expected value of 24.2 ms is observed along with false detections and inferred missed detections.

Figure 4.15 shows the histogram of those same peak spacing detections.

Figure 4.15: Histogram of the peak spacing detection’s using a 15x detection scaling factor. To generate the histogram, 100 bins were used. The expected value and integer factors of the expected value are readily observed with some false alarms present below the expected 24.2 ms.

This evidence suggests that the false alarm rate is much lower than it may appear to be in
the raw detection spacing plot. The scaling value of the moving average detector was varied to observe its impact on false alarm rates. A low scaling value of 12x is shown in Figure 4.16, while Figure 4.17 shows the results for a high scaling value of 20x.

![Detection Period Histogram](image)

Figure 4.16: Histogram of the peak spacing detections using a 12x detection scaling factor. To generate the histogram, 100 bins were used. A number of false alarms are observable.

The scaling factor of 12x results in very few missed detections, but many false alarms were observed in a cluster below the 24.2 ms expected value. In contrast, the scaling factor of 20x results in no false alarms, but many missed detections, as made evident by the far higher portion of spacings observed at an integer multiple of the expected spacing. The trade-off between probability of detection and false alarm rate is expected.

False alarms can be eliminated by applying a filter in software that disqualifies spacing detections that fall outside an upper and lower bound. The effects of missed detections can similarly be mitigated by applying a filter with bounds at integer multiples of the expected value and re-scaling them appropriately. The results of applying these filtering techniques to the 20x scaling case is shown in Figure 4.18.

Applying this filtering qualifies 1,015 of the 1,024 detections. The mean of the set was found to be 24.1971 ms with a standard deviation of 67.9 ns.
Figure 4.17: Histogram of the peak spacing detections using a 20x detection scaling factor. To generate the histogram, 100 bins were used. No false alarms are detected, but many detections were missed.

Figure 4.18: Detection history of the peak spacing using a 20x detection scaling factor. The data were filtered in software to reject spacing measurements that deviate from an integer multiple of the expected.
4.8 Signal Detection On-orbit

The high SNR of the autocorrelation peaks allows for the autonomous detection of the timing in the signal. In order to use these signals on-orbit for navigation observables, the high SNR must be maintained in the space-environment. Previous work in chapter 2 indicates that the received signal power is strong enough for on-orbit signal detection out to the lunar environment. The received signal power, coupled with the PRBS code length, show that on-orbit SNR should be strong enough for autonomous peak detection. In order to verify that this is the case, the expected SNR of the autocorrelation peaks are calculated for a lunar L1 orbit. Equation 4.3 is used to determine what the expected SNR, in dB, will be for a satellite.

\[
SNR = P_{signal} - P_{noise} \tag{4.3}
\]

The parameters of Equation 4.3 include:

\[
P_{signal} = P_t + G_{rxantenna} + G_{rxanalogchain} + G_{sp} - PL \tag{4.4}
\]

\[
P_{noise} = N_t + N_f + G_{rxanalogchain} \tag{4.5}
\]

Where:

(1) \(P_t\) is the transmitted ERP of the signal in units of dBm.

(2) \(G_{rxantenna}\) is the gain of the receiver’s antenna in dB.

(3) \(G_{rxanalogchain}\) is the analog gain of the receive chain in dB.

(4) \(G_{sp}\) is the signal processing gain in dB.

(5) \(PL\) are the path losses of the signal in dB.

(6) \(N_t\) is the thermal noise associated with the signal bandwidth in units of dBm.
(7) \( N_f \) is the noise figure of the analog receive chain in \( \text{dB} \).

For HDTV signals, the transmission power of the signals is as high as 90 \( \text{dBm} \), which is what will be used in this calculation. The signal could also be received on orbit outside the main lobe. The receiver is assumed to have 1 \( \text{dB} \) antenna gain and 30 \( \text{dB} \) of analog gain. A receiver noise figure of 2 \( \text{dB} \) is assumed. This is the listed noise figure of the AD9361 radio. For a lunar orbit, the free space loss is approximately -200 \( \text{dB} \). Equation 4.6 is used to calculate the match filter gain the signal obtains during signal processing.

\[
G_{SP} = 20 \log_{10}(t_{code}BF_{correction})
\]  

(4.6)

The parameters of Equation 4.6 include:

1. \( t_{code} \) is the autocorrelation code time, in \( \text{sec} \). For an ATSC signal this is 77.3 \( \mu\text{sec} \).

2. \( B \) is the signal bandwidth, in \( \text{Hz} \). The ATSC signal bandwidth is 6 \( \text{MHz} \).

3. \( F_{correction} \) is a correction factor that accounts for the digital approximation of the signal, non-perfect code features, windowing effects and other real-world losses.

The correction factor in Equation 4.6 is generally between 0.7 and 1 and is normally determined experimentally. In an ideal case, with a perfect correlation, Equation 4.6 shows a signal processing gain of approximately 53 \( \text{dB} \). However, the true signal processing on the signal includes anti-aliasing filtering along with an observed copy of the PRBS sequence, which includes noise. These factors, along with the digital approximation of the autocorrelation used, cause a significant drop off in signal processing gain. Using the code-segment isolated from a live-recording, approximately 21 \( \text{dB} \) of signal processing gain has been observed experimentally.

Next, using Equation 4.7, the noise floor for the ATSC signal, -106.19 \( \text{dBm} \), can be calculated.

\[
N_t = 10 \log_{10}(kTB)
\]  

(4.7)

The parameters of Equation 4.7 include:
(1) \( k \) is the Boltzmann constant, \( 1.38 \times 10^{-23} \text{JK}^{-1} \).

(2) \( T \) is the temperature, in \( K \). For this calculation, the GPS system noise temperature of 290 \( K \) is used.

(3) \( B \) is the signal bandwidth, in \( Hz \). The ATSC signal bandwidth is 6 \( MHz \).

With these values for the ATSC signal in a lunar orbit, a SNR of 16 \( dB \) could be expected on orbit. This is a value high enough for automatic detection using the algorithms described in this chapter.

4.9 Conclusions

The timing information extracted from the simulated ATSC signal correlates with what is expected from the ATSC A/53 standard. This timing information was also found to agree with the collected data to within 71.43 \( ns \) at maximum deviation. In order to obtain these timing measurements from the signal, the satellite’s on-board CPU needs to be able to either process this data at a rate of 17.2 \( MB/s \), which is the signal rate seen on the AD9361, or save the data at this rate to its hard-drive for post-processing on the ground.

The FPGA design is able to greatly reduce the computational load on the ARM CPU. Assuming a probability of detection of one and false alarm rate of zero, the FPGA will supply new detections to the processor at a rate of 41.32 \( Hz \). The power and time-stamps passed to the processor are 32-bits each, making the total data rate that the processor needs to handle 331 \( Bytes/s \). This is 0.0019244\% of the data that the processor previously needed to handle, which is a reduction in data rate of 17.1997 \( MB/s \) and five orders of magnitude in processing power.

Further, the FPGA design is shown to have the ability to extract timing information of the same accuracy as post-processing the collected data. Table 4.4 summarizes the results of these studies. Maintaining equivalent timing accuracy while significantly reducing CPU load on-board a satellite is of great importance. Due to the limited size, weight, and power (SWaP) available for instruments on-board a satellite, along with the limited and valuable CPU time, makes the
processing power savings seen with the FPGA more vital to a satellite using navigation observables from HDTV signals.

Table 4.4: Summary of the timing extracted from a raw signal using different processing techniques for the ATSC signals.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Average Timing Between Peaks (ms)</th>
<th>Deviations (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated ATSC Signals</td>
<td>24.1972</td>
<td>0</td>
</tr>
<tr>
<td>Post-Processed ATSC Signals</td>
<td>24.1971</td>
<td>71.43 (Max Deviation)</td>
</tr>
<tr>
<td>FPGA Processed ATSC Signals</td>
<td>24.1971</td>
<td>67.9 (Std Deviation)</td>
</tr>
</tbody>
</table>

Simulated HDTV signals have also been shown to be detected automatically in orbits out to the lunar environment. This allows for the possibility of autonomous satellite navigation, augmenting existing satellite navigation methods or as a back-up navigation system for a satellite, all for a low CPU cost. The CPU savings, combined with the flexibility a SDR provides for scanning wide frequency ranges, and adapting to local radio environments on the fly, allows HDTV signals to be a promising source for future satellite navigation observables.
Experiments

Further hardware and field testing was used to validate and test the signal processing techniques outlined in Chapter 4 for use in navigation solutions. Experiments were performed to further validate ATSC timing extraction methods. Low-flying Cessna aircraft flights were performed to assess signal quality for a wide range of azimuths and elevations. A high altitude balloon was used to capture the effects of high elevation and large geometric ranges. These tests allow for preliminary mapping of ATSC tower-beam patterns and demonstrate the ability to extract navigation data from HDTV towers near orbital regimes.

In order to accommodate both testing environments and accomplish the experimental objectives, the hardware must be consistent and flexible. Both experiments used the HackRF One SDR (described in Section 4.5.1) equipped with a monopole antenna to capture the HDTV signals. The Cessna flights were manned experiments while the high-altitude balloon flights were autonomous, this required each experiment use different hardware.

During the Cessna flights, the SDR is connected to a user operated laptop via USB 3.0. This laptop has GNU Radio, which is used to control the operation of the SDR during data collection. The balloon flight used the SolidRun HummingBoard (described in Section 4.5.4) to automate the control of the SDR and the data collection. The HummingBoard is loaded with GNU Radio and all of the necessary control scripts which run at power up. These control scripts are used to collect the radio signals and environmental information such as the payloads attitude information, altitude, and operating temperature during flight.
5.1 Aircraft Flights

The goal of the Cessna flights was to measure the signal strength of the transmission towers in order to better define the vertical gain patterns of the HDTV towers. Due to familiarity with the tower and its proximity to the airport, the KCNC transmission tower was chosen for examination. This is the same tower that was visited, and described in Chapter 3. The tests were performed using a Cessna 172RG Cutlass based out of the Rocky Mountain Flight School and located at the Rocky Mountain Metropolitan Airport.

Several flight paths were used to collect data from various azimuth and elevation angles to the tower. The flight paths chosen for these flights include north-south (NS), south-north (SN), and east-west (EW) passes which began below the transmission antenna from 10 mi out and rose to 2000 ft directly above the tower before descending below the antenna again. A west-east flight path was deemed unsafe to start low from that side due to the height of the Rocky Mountains to the west of the tower. These flight paths were chosen to collect signal strength data for the vertical transmission pattern along a common azimuth angle. The varying azimuthal gain pattern requires a common azimuth angle during a rising or descending path to properly map the vertical pattern. In addition to the straight line flight paths, a helical pattern was flown, beginning above the transmission tower and winding down around it. This pattern was used to collect more data from a higher elevation angle of the tower, and to see changes in signal strength from azimuth angle.

Figure 5.1 demonstrates that the signal has a strong main transmission lobe within 5° of the horizon before falling off in power. Above the main lobe the signal drops off in power exponentially. Figure 5.2 shows evidence of strong side-lobes in the tower’s vertical gain pattern. One side-lobe is seen above 6° while another is seen beginning above 14°. These side-lobes are not documented by the FCC or the transmission facility operators. The availability of side-lobes further increases the likelihood and potential of reception of these signals in space environments. This data shows that the main lobe transmission of HDTV signals is above the expected 1 MW power levels.
Figure 5.1: Relative signal power of an HDTV signal versus elevation angle. This data set was taken during an aircraft flight while climbing on a East-to-West heading with respect to the CBS KCNC ATSC transmission tower located in Golden, CO. This data set was collected on a clear day the morning of December 4, 2015.

Figure 5.2: Relative signal power of an HDTV signal versus elevation angle. This data set was taken during an aircraft flight while flying a descending circular flight pass around the CBS KCNC ATSC transmission tower located in Golden, CO. This data set was collected on a clear day the morning of December 4, 2015.

These flights only study the transmission power of the ATSC signal from a single tower. This tower suggests the signals are broadcast at, or above, 1 MW or 90 dBm and maintain strong
transmission strength above the main lobes. The KCNC tower tested is only one independent tower, however, it can be used as a general representation for other ATSC towers around the country. More flights are planned around other towers to study tower differences. These differences are important to further study since each tower is independently owned and operated.

5.2 High Altitude Weather Balloon

While data from the Cessna flights are used to map HDTV transmission vertical gain patterns, a high altitude weather balloon flight helps to characterize the quality of HDTV data in a regime more similar to LEO. By collecting data in sub-orbital environments, the ability to collect ATSC signals and extract timing information from these regimes can be examined. The high altitude weather balloon test tracked one tower at any given time and use the SBC and SDR to switch between transmission towers in order to verify tower selection capabilities. This data will allow for the verification of autonomous signal acquisition at long ranges and can be used as a testing platform for the timing extraction methods described in Chapter 4.

5.2.1 Experiment Execution

The high altitude weather balloon test was organized by Edge of Space Sciences (EoSS), a company specializing in these flight. EoSS has performed hundreds of weather balloon flights and provided the necessary materials and balloon tracking equipment needed for a successful flight. In addition to the materials provided from EoSS for the flight, a testing platform, shown in Figure 5.3, needed to be constructed. This platform needs to autonomously collect ATSC data from a variety of sources while also tracking the status of the payload throughout the flight.

The high altitude weather balloon was launched from Eaton Middle School, in Eaton CO, on February 13th, 2016, at 13:58 MST. The balloon flew for 123.35 minutes before landing in Brush, CO. With the Eaton launch location and a predicted eastbound trajectory for the balloon, ATSC transmission towers visible to the payload during the expected flight path were determined ahead of time and programmed into the SBC to track. These towers were visible to the balloon
throughout the flight while providing a N-S geometry to the tower distribution. The frequency table for this experiment, detailed in Table 5.2.1, was used by the SBC to rotate between towers being observed during flight. These towers provided a variety of different transmission locations around the northern foothills of Colorado while also ensuring the signal was viewable throughout the balloon’s flight.

The day of the experiment began with very dense cloud cover which delayed the expected launch time of 07:00 MST. In order to launch the FAA required a five mi visibility range from the launch point which the cloud cover prevented. When the high altitude weather balloon was launched, there were clear skies. The balloon then flew over one storm system before descending through clear skies. The balloon reached a maximum altitude of 28.938 km while traveling a straight line distance of 102.082 km during the experiment. Figures 5.4 and 5.5 outline the path of the balloon during the experiment. During the flight, the balloon was spinning at an average rate
Table 5.1: Transmission towers, their ERP, and corresponding center frequencies observed during February 13\textsuperscript{th}, 2016 high altitude balloon flight experiment.

<table>
<thead>
<tr>
<th>Call Sign</th>
<th>Registered Tower Location</th>
<th>Tower Latitude</th>
<th>Tower Longitude</th>
<th>ERP (kW)</th>
<th>Center Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KRMA</td>
<td>Denver</td>
<td>39° 40' 17&quot; N</td>
<td>105° 13' 06&quot; W</td>
<td>1000</td>
<td>497</td>
</tr>
<tr>
<td>KFCT</td>
<td>Fort Collins</td>
<td>40° 38' 32&quot; N</td>
<td>104° 49' 05&quot; W</td>
<td>50</td>
<td>515</td>
</tr>
<tr>
<td>KDEN</td>
<td>Longmont</td>
<td>40° 05' 59&quot; N</td>
<td>104° 54' 02&quot; W</td>
<td>800</td>
<td>563</td>
</tr>
<tr>
<td>KCNC</td>
<td>Golden</td>
<td>39° 43' 51&quot; N</td>
<td>105° 13' 54&quot; W</td>
<td>1000</td>
<td>599</td>
</tr>
<tr>
<td>KPJR</td>
<td>Greeley</td>
<td>40° 05' 59&quot; N</td>
<td>104° 54' 02&quot; W</td>
<td>700</td>
<td>617</td>
</tr>
<tr>
<td>KPXC</td>
<td>Denver</td>
<td>40° 05' 59&quot; N</td>
<td>104° 54' 02&quot; W</td>
<td>1000</td>
<td>647</td>
</tr>
</tbody>
</table>

of 0.5313 rad/sec along the vertical axis. Figure 5.6 represents the attitude rates of the payload during the experiment.

![Image](image-url)

Figure 5.4: Inertial path of the high altitude weather balloon in relation to the ATSC towers being tracked during the experiment.

The payload temperature is also monitored during the experiment and can be seen in Figure 5.2.1. The temperature needs to be tracked in case of system shut down due to overheating or freezing. The temperature of the payload was expected to vary throughout the flight due to the changing temperature and pressure in the environment the payload flew through and the heat sources within the payload. As the payload rises to its maximum height the atmosphere will thin.
out. This thinning causes the atmosphere to cool however it also reduces heat convection. In the upper atmosphere, before the balloon pops and payload falls back to the surface the main heat transfer type is radiation. Throughout the flight the SBCs and SDRs within the payload are also generating heat constantly after they are turned on.

These factors leads to an intial heating of the payload while conduction is occurring in the
payload and the local atmosphere is warm slowing convection. As the atmosphere becomes cooler the heat being generated by the payload is convected out of the system and it cools down. Once the payload is high enough that radiation is the driving type of heat transfer the payload begins to heat up again. This is due to the payload not having a strong radiator due to its insulation. When the balloon pops it continues to heat until it has fallen far enough for the atmosphere to be dense enough for convection to begin again. Finally as the balloon completes its descent it cools down until the warm atmosphere once again reduces the ability to convect heat off the payload faster then it is generating heat.

![Balloon Temp](image1.png)  ![Balloon Altitude](image2.png)

(a) Payload temperature, observed by sensors within the payload, during the high altitude weather balloon experiment. (b) Payload altitude, observed by sensors within the payload, during the high altitude weather balloon experiment.

The SBC is programmed to collect data from a single frequency band for one second, sleep for half of a second, then go to the next frequency in the table. After every cycle through the frequency table, the SBC sleeps for three seconds before starting again from the beginning of the table. This data collection pattern was chosen to help ensure that data would be collected from all the towers in the frequency table during the flight, while also staying within the hard-drive space available on board the testing platform.

Figure 5.7 shows the elevation angles seen by the payload to the transmission towers while Figure 5.8 details the range from the payload to the transmission towers during the flight. It can be seen that the maximum elevation angle seen by the payload was $21^\circ$ from the KPXC tower and the maximum range from the payload to a tower was 155 km.
5.2.2 Observed Signal SNR

The autocorrelation SNR of the signal collected throughout the balloon flight was calculated to validate the signal processing techniques from Chapter 4 in sub-orbital space. Figures 5.9 and 5.10 show the SNR observed during flight from the towers with the best and worst SNR. Figure 5.9 illustrates that the maximum SNR is seen from the KCNC tower and averages approximately nine $dB$ above the noise floor, while the lowest SNR is seen from the KPJR tower and averages approximately five $dB$ above the noise floor. During the ascending phase of the experiment the SNR drops from a peak when it is in the main lobe of the transmission tower to a minimum when
at its highest elevation angle and range from the tower. The valley in the SNR is, on average, five \( dB \) lower than the peak value.

![Figure 5.9: SNR calculated from the data collected by the payload from the KRMA tower during the high altitude weather balloon experiment.](image1)

![Figure 5.10: SNR calculated from the data collected by the payload from the KDEN tower during the high altitude weather balloon experiment.](image2)

These autocorrelation peaks are lower than expected from the analysis performed in Chap-
ters\textsuperscript{2} and Chapter\textsuperscript{4} These differences need to be further investigated to determine if the differences come from using a receiving antenna with no gain and the tracking of some towers with ERP below the one MW assumed for those studies or from other error sources that were unmodeled in the simulations.

5.2.3 Extracted Signal Timing

With the collected data, the signal timing information was extracted. The resulting timing information can be seen in Table 5.2. The balloon flight data shows that the average median absolute deviation for all frequencies observed during the flight is 43.590 ns. The highest deviations seen came from the KPXC tower with a median absolute deviation of 67.953 ns while the lowest deviations came from the KRMA tower with a median absolute deviation of 30.887 ns.

Table 5.2: Summary of the timing extracted from data collected during high-altitude balloon flight.

<table>
<thead>
<tr>
<th>Center Frequency (MHz)</th>
<th>Average Timing Between Peaks (ms)</th>
<th>Median Absolute Deviations (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>497</td>
<td>24.19717</td>
<td>30.89</td>
</tr>
<tr>
<td>515</td>
<td>24.19721</td>
<td>32.09</td>
</tr>
<tr>
<td>563</td>
<td>24.19711</td>
<td>44.13</td>
</tr>
<tr>
<td>599</td>
<td>24.19719</td>
<td>49.42</td>
</tr>
<tr>
<td>617</td>
<td>24.19723</td>
<td>37.07</td>
</tr>
<tr>
<td>647</td>
<td>24.19717</td>
<td>67.95</td>
</tr>
</tbody>
</table>

This data shows that even with the minimum SNR seen during flight, the signal processing techniques discussed in Chapter\textsuperscript{4} successfully detected the peaks and extracted timing information from the data. The timing extracted from this data shows that precise timing information can be extracted autonomously in sub-orbital space.

5.3 Conclusions

These experiments demonstrate several important pieces of information for HDNav. The first is that the KCNC tower, studied with a Cessna, drops off exponentially in broadcast power above
its main lobe; however, it does contain side-lobes which can be exploited for navigation purposes. The balloon flight shows that with a low-gain monopole antenna and an imperfect recording of the PRBS codes, the HDTV signals can be observed out to sub orbital distances, even when tracking low power transmission towers. These tests are encouraging, though further tests mapping other transmission tower gain patterns are planned. This would help identify differences in gain patterns between HDTV towers. More high altitude testing is planned to further test autonomous tracking and timing extraction from the towers in sub-orbital regimes.
Chapter 6

Navigation Simulations

So far, it has been demonstrated that HDTV signals provide strong orbital coverage and are broadcast at high enough powers to be received on orbit. It has also been shown that precise timing information can be extracted from the signals. A series of navigation simulations must be performed to demonstrate HDNav’s suitability for OD. This chapter will discuss the navigation observables that can be extracted from HDTV signals and will investigate the navigation performance that can be achieved using HDNav. The navigation solutions for satellites in several different lunar orbits, including L₁, L₂, and distant retrograde orbits (DROs), will be discussed. Data for these simulations is processed using both an extended Kalman filter (EKF) and a square root information filter (SRIF). Lunar orbits are the focus of this work due to the current interest in lunar orbits. Missions such as ARM and Orion, among others, are currently of interest to the space community. Additionally private companies (such as SpaceX and ULA) are interested in lunar bases, as well as using lunar orbits as staging points to send humans further out into the solar system.

6.1 Navigation Observables

The HDNav system, as studied here, yields two different navigation observables from the data processing techniques described in Chapter 4. By performing the aforementioned autocorrelation methods, the relative signal timing can be tracked after signal acquisition. In the case of ATSC signals each signal will need to be isolated on orbit since a satellite will be in the presence of multiple signals at all times. By monitoring the reception time of each FSS, and the time since the last
FSS, ranging and Doppler information can be extracted. The navigation observables require that the HDTV transmitters maintain the synchronization levels required by the ATSC Standard for Transmitter Synchronization. If using DVB-T or ISDB-T HDTV signals, the observables require these signals to have strong stability limits. Each measurement will have both noise and biases in them. The biases and noise occur due to clock instability, thermal effects on the receiving antenna, signal errors created during travel through different media environments, among other sources. This section outlines the navigation observables used by the HDNav system simulations performed for this work.

6.1.1 Doppler

The first navigation observable that can be used by HDNav is a Doppler measurement. For satellite navigation, a Doppler count measurement is traditionally used. However, a different approach is taken for HDNav. Since the bulk frequency shift of the signal causes the entire signal code to shift, a Doppler measurement can be computed from the time between successive autocorrelation peaks. By comparing the measured time between peak detections to the expected time between peak detections, a bulk frequency shift of the signal can be computed. When the bulk frequency shift is integrated over several time steps the errors in the measurement can be reduced by a factor of $1/\sqrt{N}$ time steps. This is the Doppler measurement in the filters; the observed peak timing difference is defined by Equation (6.1).

$$t_{diff} = t_{obs} - t_{exp}$$ (6.1)

$$t_{diff} = \frac{\dot{\rho} + \dot{\rho}_{bias}}{c + \dot{\rho} + \dot{\rho}_{bias}} t_{code}$$ (6.2)

$$\dot{\rho} = \frac{(\vec{r}_{sat} - \vec{r}_{trans}) \cdot (\dot{\vec{r}}_{sat} - \dot{\vec{r}}_{trans})}{| (\vec{r}_{sat} - \vec{r}_{trans}) |}$$ (6.3)

The parameters of Equations (6.1) - (6.3) include:
(1) \( \vec{r}_i : [x_i, y_i, z_i] \) are Earth-centered inertial Cartesian position vectors for the satellite (sat) and transmission tower (trans).

(2) \( \dot{\vec{r}}_i : [\dot{x}_i, \dot{y}_i, \dot{z}_i] \) are Earth-centered inertial Cartesian velocity vectors for the satellite (sat) and transmission tower (trans).

(3) \( t_{code} \) is the expected timing between autocorrelation peaks for the signal. In the case of ATSC signals, this is 24.2 ms.

(4) \( \dot{\rho}_{bias} \) is the range-rate bias unique to each pass and HDTV transmitting antenna.

### 6.1.2 Pseudorange

A pseudorange measurement can be obtained from the autocorrelation peak timing in the HDTV signal. An autocorrelation detection tells the filter where within a frame the signal currently is. While this phase observation of the signal yields the location of the receiver within a frame the integer number of wavelengths between the satellite and the receiver during the travel time in not known. This cycle ambiguity needs to be combined with the phase measurement in order to obtain the pseudorange measurement described in Equation (6.4). The cycle ambiguity is unknown to the filter and therefore must be an estimated state in order to maintain accurate positioning.

\[
p = \frac{\rho + \rho_{bias}}{\lambda} + n
\]  

\[
\rho_i = \sqrt{(x_{sat} - x_{trans})^2 + (y_{sat} - y_{trans})^2 + (z_{sat} - z_{trans})^2}
\]  

The parameters of Equation (6.4) include:

(1) \( \rho_{bias} \) is the range bias unique to each pass and HDTV transmitting antenna.

(2) \( \lambda \) is the HDTV signal wavelength.

(3) \( n \) is the cycle ambiguity.
6.1.3 Differential Time Offset

Another observable that can be extracted from the HDTV signal is a differential time offset (DTO) measurement. DTO is used instead of a pseudorange measurement in these simulations due to its stronger information content. A DTO measurement contains the information from two pseudorange measurements. If both DTO and pseudorange measurements are used the filter obtains the same informational content but that information gets diluted due to the extra measurement sharing the information. By using DTO instead of pseudorange additional clock biases from the receiver do not need to be estimated since the two range measurements that make up DTO eliminate the additional biases in the information.

Transmitted HDTV signals are synchronized to within 50 ns of each other. Due to different tower locations and therefore different path lengths, the peak detections will occur at different times for different towers. This difference in peak detection time between two towers is the navigation observable DTO. Traditionally DTO measurements are a two-way sub-component of a time difference of arrival (TDOA) measurement, which is defined by Equation (6.6). However, when using HDTV signals, there is only a 1-way measurement because there is no downlink. This turns the DTO calculation into Equation (6.7). The biases seen in Equation (6.7) are due to the transmitter, not receiver.

\[
DTO_{\text{twoway}} = \frac{1}{c} \left[ (\rho_{2_{\text{up}}} - \rho_{2_{\text{down}}}) - (\rho_{1_{\text{up}}} - \rho_{1_{\text{down}}}) \right] \tag{6.6}
\]

\[
DTO_{\text{oneway}} = \frac{1}{c} \left[ (\rho_{2_{\text{up}}} + \rho_{2_{\text{bias}}}) - (\rho_{1_{\text{up}}} + \rho_{1_{\text{bias}}}) \right] \tag{6.7}
\]

Where \(\rho_i\) is the light-time range, between transmission tower \(i\) and the spacecraft, defined in Equation (6.5). For the simulations in these studies the instaneous range is used.

Since TDOA, and therefore DTO, has observability issues for use with satellite navigation problems, DTO needs to be used in conjunction with Doppler measurements in the simulations. These observability issues are seen when a scenario does not have enough tracking station calibrators.
monitoring the system or a scenario does not have enough variability in the geometry of its satellites or tracking stations. A DTO measurement can only constrain a satellites' location to a hyperboloid, as larger geometric diversity is introduced into the system the better the location can therefore be determined. While DTO can theoretically be used as the sole measurement type, the geometry of the system effects the observability. If there is not enough orbital, or geographic, diversity in the system then a filter is unable to converge on a unique solution for the system.

6.2 Signal Simulator

Signal simulation code is developed to help validate the feasibility of the signal processing and signal detection techniques that are needed on orbiti, in order to develop high fidelity navigation simulations. This simulation software development can also be used to inform the design of a finalized, field-able system. The simulation modifies an idealized signal based on the physical parameters of the scenario. The resulting signal can then be fed into the signal processing chain for validation. The simulation does not model receiver clock errors that would be seen in a real receiver. Further work needs to be done to assess the effects of receiver clock errors.

- Transmitter ERP
- Receiver Gain (Antenna and Electronic)
- Path Loss
- Time Delay
- Bulk Doppler Shift
- Thermal Noise
- Receiver Noise Figure

The original signal is an ideal template of the signal of interest sampled at baseband with no noise. Physical effects are computed based on the simulation parameters and applied to this
ideal template. The gain of the receiving system and transmitter ERP are set by the user as a parameter in the simulation. Path loss and time delay are calculated based on the distance from transmitter to receiver. The path loss, receiver gain, and transmitter ERP are used to compute the power the receiver should see at the digitization step. The path loss, $L_{path}$, is calculated using Equation (6.8) while the receiver gain and transmitter ERP are given based on the characteristics of those antenna. Based on the characteristics of the receiver’s analog to digital converters, this value is converted to a scaling factor that is applied to the ideal template of the signal of interest.

Time delay is applied as a circular shift in the digital samples. Currently, the time delay is applied as a whole number multiple of the sampling period. Fractional time shifts can be applied using frequency domain techniques, but have not been explored in detail for this simulation.

$$L_{path} = 20 \log_{10} \left( \frac{\lambda}{4\pi R} \right)$$  \hspace{1cm} (6.8)

Where:

1. $\lambda$ is the wavelength of the transmitted signals center frequency.
2. $R$ is the range between the receiver and transmitter.

The Doppler effects are modeled as a bulk frequency and code shift. The velocity vector of the receiver is used to compute the radial velocity between receiver and transmitter. Doppler shift is computed using this velocity and the center frequency of the band of interest. A frequency shift is computed and GNU Radio\cite{42} is used to generate a complex vector at this frequency. This shift is applied to the now-scaled and delayed signal using the computed vector and a complex multiplication. Equation (6.9) is used to calculate the bulk frequency shift.

$$F_{shifted} = \frac{v_r}{c} f_c$$  \hspace{1cm} (6.9)

Where:

1. $v_r$ is the radial velocity between receiver and transmitter.
(2) $f_c$ is the transmitted signals center frequency.

To assess signal detection algorithms, the thermal noise and receiver noise figure are simulated. The power level of the thermal noise, calculated using Equation (6.10), and noise figure, are calculated in $dBm$. A random vector is generated with the necessary amplitude to approximate the required noise power. This vector is added to the scaled and shifted signal.

$$N_{thermal} = 10 \log_{10}(k_B T B) + 30$$

(6.10)

Where:

(1) $k_B$ is the Boltzmann constant.

(2) $T$ is the receiver noise temperature, in K.

(3) $B$ is the bandwidth of the signal, in Hz.

All of these processes are then combined to generate the final signal received by the satellite. The final signal generated by this signal processing chain, visualized in Figure 6.1, is then processed using the algorithms discussed in Chapter 4. The resulting timing information is used by the filters in the navigation simulations as the Doppler and DTO observations.

![Signal processing chain for signal simulator.](image)

Figure 6.1: Signal processing chain for signal simulator.
6.3 Simulation Orbits

The navigation simulations perform filtering on satellite orbits from three classes of lunar orbital families. Distant retrograde orbits (DROs), lunar L$_1$ halo orbits, and lunar L$_2$ halo orbits are used in these studies. These orbital families are currently of interest to NASA for a variety of missions. DROs are of interest for the Asteroid Robotic Redirect Mission (ARRM), among others, due to their long term-stability, on the order of hundreds of years. Lunar libration orbits are of interest for their potential as staging points for manned missions to Mars, as well as for crewed deep-space stations and lunar exploration.

6.3.1 DRO

DROs are simple-periodic symmetrical orbits which are stable over long time-scales. A DRO is a retrograde orbit around a secondary body whose mass is small relative to the primary. DROs are solutions of the circular restricted three-body problem, classified in family $f$, according to Henon’s classification scheme. Figure 6.2 shows an example DRO in the Earth-Moon rotating frame.

6.3.2 Lunar Libration Halo Orbits

Lunar libration halo orbits have many benefits for use in satellite missions. Halo orbits can utilize any number of low-energy transfers, through the existence of stable and unstable manifolds, to enter or depart the orbit. This allows for inexpensive re-positioning of a satellite during a mission. The Earth is continuously visible to an object in a lunar libration halo orbit that has a large enough z-amplitude, which affords for greater tracking potential provided by uninterrupted communication links to the Earth’s surface. Libration orbits provide a potential staging location for lunar exploration missions as well. Figure 6.3 shows an example L$_2$ orbit in the Earth-Moon rotating frame.
Figure 6.2: Example DRO about the Moon.

Figure 6.3: Example of a lunar L$_2$ orbit in the Earth-Moon rotating frame.
6.4 Simulation Tower Locations

Two different navigation simulation scenarios are studied in this work. The first compares filter performance when processing Doppler only to the performance when using a combination of Doppler and DTO. For the Doppler only scenarios, 31 transmission towers are placed throughout North America. Only eight towers are used for the Doppler plus DTO simulations. This is to reduce the number of potential DTO measurements that are generated for the orbit. Both Doppler and DTO are used for the Monte Carlo simulations. The eight towers chosen for the Doppler and DTO cases have large north-south and east-west separation which helps to optimize observation geometry. In order to better account for hardware limitations, in all simulations it is assumed that the satellite can only track four towers at any given time which simulates a satellite receiver which has a limited number of channels. Figure 6.4 shows the locations of all of the transmission towers used for these simulations.

Figure 6.4: Tower locations used in the simulations. Towers in yellow are used in the only Doppler scenario while towers in red are used for the DTO plus Doppler scenarios.
6.5 Filter Setup

This section outlines and describes the dynamical models and filters that are used in this work.

6.5.1 Observations

Using the HDTV tower locations presented in the previous section, observations were generated for sample \( L_1 \), \( L_2 \) and DRO orbits. The variable parameters used in the signal simulator are the same as seen in Section 4.8 and can be found in Table 6.1. The remaining signal characteristics were set to match the GPS block III satellites. The range and range-rate biases are unique to each tower, and are sampled from \( N(0, 30) \) and \( N(0, 5) \) distributions, with units of \( m \) and \( mm/s \), respectively. 25 \( m \) and 3 \( mm/s \) of white noise are added to the scalar range and range-rates from Equations 6.5 & 6.3. All of the biases and noise values are determined from the < 1 ppb expected performance of the transmission tower oscillator; if the noise values seen on orbit are greater than the values used here navigation accuracy will degrade.

Table 6.1: Signal simulator parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{\text{center}} )</td>
<td>599 GHz</td>
</tr>
<tr>
<td>( G_t )</td>
<td>60 dB</td>
</tr>
<tr>
<td>( G_r )</td>
<td>31 dB</td>
</tr>
<tr>
<td>( N_f )</td>
<td>2 dB</td>
</tr>
</tbody>
</table>

6.5.2 Dynamical Models

The trajectories are built using MATLAB and include non-spherical gravity, third-body, and solar radiation pressure perturbations. A full summary of the dynamical system can be found in Table 6.2. An independent orbit determination software suite (written in C++) was used to process the results. This was done for two reasons: 1) to improve performance for Monte Carlo simulations and 2) to validate code and methodology. The dynamical system was intentionally
mis-modeled in order to better approximate real-world conditions. The degree and order of the spherical harmonic gravity field was reduced and all third-body effects aside from the Sun and the Moon were removed. A summary of the force models used in the orbit determination filter is shown in Table 6.2

Table 6.2: Summary of force model settings that were used to generate the truth trajectory and observations.

<table>
<thead>
<tr>
<th>Force Model</th>
<th>Parameter</th>
<th>Truth Value</th>
<th>Filter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical Harmonics</td>
<td>Degree</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Order</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Solar Radiation Pressure</td>
<td>$C_r$</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Third Bodies</td>
<td>Point Mass</td>
<td>Full Ephemeris</td>
<td>Sun</td>
</tr>
</tbody>
</table>

6.5.3 Filters

In an attempt to fully characterize the performance of HDTV observables, navigation simulations were performed using two separate filters. The two filters chosen are the standard Extended Kalman Filter (EKF) and the sequential Square Root Information Filter (SRIF).  

6.5.3.1 Extended Kalman Filter

The EKF, like most sequential estimation algorithms, consists of a time-update and a measurement-update which will be explained throughout this section. The EKF is based off of the conventional Kalman Filter, where the time update propagates the reference trajectory, estimated state deviations and covariance to the time of the current observation:

**Time-Update:**

$$\bar{x}_i = \Phi(t_i, t_{i-1}) \bar{x}_{i-1}$$  \hspace{1cm} (6.11)
\[ P_i = \Phi(t_i, t_{i-1}) P_{i-1} \Phi^T(t_i, t_{i-1}) \]  
\[ (6.12) \]

The parameters of which include:

- \( \Phi \) is the state transition matrix, and can be found using Equation 6.13.
- \( \bar{x}_i \) is the time updated state deviation vector. It is \( \hat{x}_{i-1} \) propagated to time \( i \).
- \( \hat{x}_i \) is the state deviation vector of the filter at time \( i \).
- \( \hat{x}_{i-1} \) is the preceding estimate of the state deviation vector.
- \( \bar{P} \) is the time updated covariance matrix.
- \( P_{i-1} \) is the estimated covariance matrix based on preceding measurements.

\[ \dot{\Phi}(t, t_{i-1}) = A(t) \Phi(t, t_{i-1}) \]  
\[ (6.13) \]

The parameter \( A \) is the Jacobian of the differential equation of the dynamical system with respect to the estimated state vector, evaluated on the reference trajectory, defined by Equation 6.14.

\[ A(t) = \left[ \frac{\partial \hat{X}(X, t)}{\partial X} \right]^* \]  
\[ (6.14) \]

The measurement update updates the estimated state deviations using information gained from the current measurement.

**Measurement-Update:**

\[ \hat{x}_i = \bar{x}_i + K_i [y_i - \bar{H}_i \bar{x}_i] \]  
\[ (6.15) \]

\[ P_i = (I - K_i \bar{H}_i) P_{i} (I - K_i \bar{H})^T + KRK^T \]  
\[ (6.16) \]

Where:
• $K_i$ is the Kalman gain.

• $\tilde{H}_i$ is the measurement partials matrix. The partials used in these simulations can be found in Appendices C & D.

• $R$ is the measurement noise covariance matrix.

• $y_i$ is the prefit residual.

Whereas the conventional Kalman Filter simply updates the estimate state deviations and covariance, the extended version updates the reference trajectory as seen in Equation (6.2).

\[ X_{new}^* = X_{old}^* + \hat{x}_i \]  

(6.17)

Using an EKF instead of a CKF present several benefits including the ability to use it longer than a CKF because the reference trajectory shouldn’t leave the linear regime. This allows the filter to work beyond the point where linearization of the system would break down. The use of an EKF also allows for the use of the filter in the presence of unmodeled secular errors in the system. However the use of an EKF also presents several potential issues, including the ability to diverge if it has poor \textit{a priori} knowledge or if the filter is overconfident in its measurements. Normally when using an EKF the user will run a CKF for a period of time in order to let the solution converge before switching over to and EKF, or the EKF could be started on an already converged solution. Please refer to Appendix A for a more complete discussion on the Extended Kalman Filter. Refer to Appendices C & D for the partial derivatives in the $\tilde{H}$ matrices.

6.5.3.2 Square Root Information Filter

The sequential SRIF also consists of a time-update and a measurement-update, however instead of operating on the covariance matrix directly, the filter is formulated in terms of the square root of the information matrix. The benefit is two-fold: 1) this method avoids the inversion of the information matrix and 2) it halves the condition number of the information matrix, both of
which increase numerical stability and help mitigate divergence issues that arise when performing floating point arithmetic.

**Time-Update:**

\[
\bar{R}_i = R_{i-1} \Phi^{-1}(t_i, t_{i-1})
\] (6.18)

\[
\bar{b}_i = \bar{R}_{i-1} \bar{x}_{i-1}
\] (6.19)

Where \( R_i \) is the square root (Cholesky decomposition)\textsuperscript{106} of the information matrix.

**Measurement-Update:**

\[
\bar{T}_i \begin{bmatrix} \bar{R}_i & \bar{b}_i \\ H_i & y_i \end{bmatrix} = \begin{bmatrix} \hat{R}_i & \hat{b}_i \\ 0 & \hat{e}_i \end{bmatrix}
\] (6.20)

\[
\hat{x}_i = \hat{R}_i^{-1} \hat{b}_i
\] (6.21)

Where \( H_i \) and \( y_i \) are the *whitened* measurement partials matrix and the *whitened* prefit residual, respectively. \( \bar{T}_i \) indicates a series of orthogonal transformations\textsuperscript{107} Note that in this work the reference trajectory is also updated, as seen in the EKF. Please refer to Appendix B for a more complete discussion on the Square Root Information Filter.

### 6.5.3.3 Estimated State & *a priori* Initialization

In this work, the estimated state includes the inertial position and velocity of the spacecraft, the spacecraft’s coefficient of reflectivity for solar radiation pressure, and range and range-rate biases for each tower:

\[
\hat{X}_{23x1} = [\mathbf{r} \ \dot{\mathbf{r}} \ C_r \ b_1 \ \dot{b}_1 \ \ldots \ b_n \ \dot{b}_n]^T
\] (6.22)
In these simulations there are no receiver clock states estimated. These are states that would need to be estimated due to the errors an imperfect oscillator would add to observations in the HDNav system.

For cases where only DTO measurements are processed, the ˙\( b_i \) terms are excluded from the state vector. Initial orbit determination (IOD) is simulated by initializing the filter with large perturbations to the estimated state and a correspondingly large a priori covariance. For all cases (L₁, L₂, DRO), the initial position deviation was sampled from a normal distribution of \( N(0, 200) \) m, and the velocity deviations were sampled from \( N(0, 2) \) cm/s. The initial range and range-rate biases were set to zero. 6σ values of \( N(0, 1200) \) m and \( N(0, 12) \) cm/s were found to be the breaking point at which the filters diverged. 6σ values for deviations were used because the Monte Carlos were designed to sample out to at least 6σ.

6.6 Doppler vs. DTO Navigation Simulation Results

The strength of the HDNav observables can be seen in the performance of navigation filters. Cases where a satellite uses only Doppler measurements, and where a satellite uses both Doppler and DTO measurements in an EKF, are presented here. A DTO-only case was not performed due to the observability issues discussed in Section 6.1.3.

For each simulation performed in these studies the states errors and 3σ covariance are presented. The state errors are determined by differencing the filters estimated state with the truth trajectory used to generate the measurements. The 3σ covariance is the filters 99.7% estimate of the state. The state errors seen from the filter should be bounded by the covariance envelope 99.7% of the time. For each simulation the filter is seen to have converged upon a solution over time. When the both the covariance envelope and state errors have plateaued the filter is considered to have converged upon the solution. The resulting magnitude of the the state errors and size of the covariance envelope are both functions of the dynamic mismodelling in the sytem and the noise seen in the measurements. In order to better quantify the performance of the filter the root-mean-square (RMS) of the solution over the final 2.5 days of the simulation is used as a way to quantify
the filters overall performance.

When only Doppler measurements are used the filter converges after approximately 8 days with a final-two-day position RMS of 104.75 m and a final two day velocity RMS of 0.243 mm/s. For the Doppler and DTO case, the filter converges to final two day RMS values of 28.1 m and 0.162 mm/s for position and velocity respectively. It can be seen that the filter converges slower in the inertial z-direction, this is due to the z direction being approximately perpendicular to the line of sight at all times. The results of these simulations can be seen in Figures 6.5 and 6.6.

![Figure 6.5: Evolution of the state covariance envelopes for a 14.5 day simulation using an EKF. For this simulation only the Doppler measurement observables are processed by the filter.](image)

It can be seen in the Doppler-only case that the velocity covariance converges and settles early on while the position estimate has more variability in it. The velocity estimates converge to similar accuracies for both the Doppler-only and Doppler plus DTO cases. This is expected behavior since the DTO measurement does not directly contain any extra information about the satellite’s velocity, over time the velocity can be constrained though. The position estimate from the Doppler plus DTO case is better than the Doppler-only case. The position covariance takes more than twice as long to converge and converges to a worse solution overall using only Doppler.
6.7 Monte Carlo Navigation Simulation Results

The state estimates and covariances determined in the Monte Carlo simulations are processed in several ways. The final state errors from each run are then condensed using both the 99th percentile and RMS value for each state error. The 99th percentile and RMS errors are then processed using support vector machines (SVM) to determine 1-, 2-, and 3-σ error bounds in the filter solutions.

6.7.1 Support Vector Machines

SVMs are a type of machine learning algorithm that are commonly used to approximate the shape of data distributions and can be used to determine if a data point belongs to the same distribution as other points. SVMs perform classification tasks by constructing hyperplanes in a multidimensional space that separate cases into different classes, shown in Figure 6.7. They support both regression and classification tasks and can handle multiple continuous and categorical variables. For non-linearly separable data, SVMs use a specified kernel to map the data into a higher dimension that can be separated by a hyperplane. SVMs use support vectors, which are the data points that lie closest to the hyperplane to determine the optimal solution. The SVM defines
a boundary by maximizing the margin between the support vectors on each side. For the Monte Carlo simulations, a Gaussian radial basis function (RBF) is used. The RBF kernel is defined by Equation (6.23).

\[ K(x, x') = \exp\left(-\frac{1}{2} \gamma \|x - x'\|^2 \right) \] (6.23)

Figure 6.7: The top image shows a SVM using linear separation. The bottom image shows the mapping of data into higher dimension to be separated by a hyperplane.

Where \( \gamma = 1/(2\sigma^2) \), and \( \sigma \) is a tuning parameter. Using the RBF kernel, the SVM determines which data points fit within 68.27%, 95.45%, and 99.73% boundaries. These distributions can then be used to quantify the expected performance of HDNav.
6.7.2 Initial Orbit Determination Simulations

The first set of navigation simulations performed are initial orbit determination studies. These Monte Carlo simulations were run sampling from the distributions discussed in Section 6.5.3.3. For each orbit type and each filter type, EKF and SRIF, 20,070 individual navigation simulation cases were run. The JANUS supercomputer at the University of Colorado - Boulder is used for each of these Monte Carlo simulations. The JANUS supercomputer is set-up with 1368 compute nodes, each containing 12 cores, for a total 16,416 usable cores. The JANUS system runs the Redhat 6 Enterprise operating system. The results of these Monte Carlo simulations are presented here.

6.7.2.1 DRO

Both the EKF and SRIF cases produce similar results with each filter takes approximately 9 days to fully converge. The state errors stay bounded throughout the simulation by the $3\sigma$ covariance envelopes. Figures 6.8 and 6.9 show sample $3\sigma$ covariance envelopes and state errors as they evolve over the full 14.5 days of the simulation.

![Figure 6.8: Evolution of the state covariance envelopes during a 14.5 day IOD DRO simulation using an EKF.](image)

From the Monte Carlo simulations, the final 2.5 day $3\sigma$ position covariance RSS for the EKF is $109.27 \, m$ and the final 2.5 day $3\sigma$ velocity covariance RSS is $1.19 \, mm/s$. For the SRIF the final
2.5 day $3\sigma$ position covariance RSS 109.24 m and the final 2.5 day $3\sigma$ velocity covariance RSS is 1.185 mm/s. The 99th percentile of the norm of the position-state errors averages 35 m and 0.25 mm/s for velocity. The SRIF is seen to have fewer outliers than the EKF and has a denser peak in the error histogram. The error histogram is skewed right, with the position histogram skewed further right. This suggests that the filter tends to reach an optimal convergence, except when sampled from very large initial perturbations. The filter has the worst state estimates in the $z$ and $v_y$ directions and the best estimates in the $x$ and $v_x$ directions. The results from the Monte Carlo simulations can be seen in Figures 6.10 and 6.11.

### 6.7.2.2 L₁ Halo Orbit

For the L₁ case, the state errors stay bounded throughout the simulation by the $3\sigma$ covariance envelopes. Figures 6.12 and 6.13 show sample $3\sigma$ covariance envelopes and state errors over the 14.5 days of the simulation.

From the Monte Carlo simulations, the final 2.5 day $3\sigma$ position covariance RSS for the EKF is 157.67 m and the final 2.5 day $3\sigma$ velocity covariance RSS is 1.291 mm/s. For the SRIF the final 2.5 day $3\sigma$ position covariance RSS 157.13 m and the final 2.5 day $3\sigma$ velocity covariance RSS is
Figure 6.10: 99\textsuperscript{th} percentile of position-state errors during the final 2.5 days of the 14.5 day IOD Monte Carlo simulations for a DRO. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.

![Diagram](image1)

(a) EKF  
(b) SRIF

Figure 6.11: 99\textsuperscript{th} percentile of velocity-state errors during the final 2.5 days of the 14.5 day IOD Monte Carlo simulations for a DRO. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.

![Diagram](image2)

(a) EKF  
(b) SRIF

1.288 mm/s. The 99\textsuperscript{th} percentile of the norm of the position-state errors averages 67 m and 0.78 mm/s for velocity. The EKF is seen to have fewer outliers than the SRIF and has a denser peak.
in the error histogram. The error histogram has a Gaussian shape but has a small skew right for position and is skewed right for velocity. The $L_1$ state estimates are worse than those seen in the DRO. This is expected behavior of the filter due to the more unstable nature of a $L_1$ orbit. The filter has the worst state estimates in the $y$ and $v_z$ directions and the best estimates in the $x$ and $v_x$ directions. The results from the Monte Carlo simulations can be seen in Figures 6.14 and 6.15.
Figure 6.14: 99th percentile of position-state errors during the final 2.5 days of the 14.5 day IOD Monte Carlo simulations for a L1 orbit. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.

Figure 6.15: 99th percentile of velocity-state errors during the final 2.5 days of the 14.5 day IOD Monte Carlo simulations for a L1 orbit. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.
6.7.2.3 L₂ Halo Orbit

For the L₂ case, the state errors stay bounded throughout the simulation by the $3\sigma$ covariance envelopes. Figures 6.16 and 6.17 show sample $3\sigma$ covariance envelopes and state errors over the 14.5 days of the simulation.

![Figure 6.16](image1.png) ![Figure 6.17](image2.png)

Figure 6.16: Evolution of the state covariance envelopes during a 14.5 day IOD L₂ simulation using an EKF.

Figure 6.17: Evolution of the state covariance envelopes during a 14.5 day IOD L₂ simulation using a SRIF.

From the Monte Carlo simulations, the final 2.5 day $3\sigma$ position covariance RSS for the EKF
is 180.86 m and the final 2.5 day 3σ velocity covariance RSS is 1.421 mm/s. For the SRIF the final 2.5 day 3σ position covariance RSS 180.88 m and the final 2.5 day 3σ velocity covariance RSS is 1.418 mm/s. The 99th percentile of the norm of the position-state errors averages 85 m and 0.71 mm/s for velocity. The EKF and SRIF are seen to have similar peak densities for the L2 case. The error histogram is skewed right for position and is more Gaussian with a small skew right for velocity. The L2 state estimates are on the same order of magnitude as the L1 orbit, which is expected given the similarities of the orbit types. The filter has the worst state estimates in the z and vz directions and the best estimates in the x and vx directions. The results from the Monte Carlo simulations can be seen in Figures 6.18 and 6.19.

Figure 6.18: 99th percentile of position-state errors during the final 2.5 days of the 14.5 day IOD Monte Carlo simulations for a L2 orbit. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.

6.7.3 Steady-State Orbit Determination Simulations

The second set of navigation simulations performed are steady orbit determination studies. These Monte Carlo simulations were run sampling from a distribution of errors determined by the IOD simulations. The average final errors for each coordinate system were chosen to sample from
for initial errors. For the steady-state cases, the simulation was run for 9.5 days instead of the 14.5 days in the IOD study. For each orbit type, DRO, L₁, and L₂, and each filter type, EKF and SRIF, 10,035 individual navigation simulation cases were run. A lower number of samples were chosen because the steady-state case should begin converged so that its performance over a shorter time frame will still show the filters overall accuracy. Also, allocation constraints on the JANUS supercomputer used for these Monte Carlo simulations required a shorter simulation time-frame. The results of these Monte Carlo simulations are presented here.

### 6.7.3.1 DRO

For the DRO case, the state errors stay bounded throughout the simulation by the $3\sigma$ covariance envelopes. Figures 6.20 and 6.21 show sample $3\sigma$ covariance envelopes and state errors over the 9.25 days of the simulation.

From the Monte Carlo simulations, the final 2.5 day $3\sigma$ position covariance RSS for the EKF is 85.34 m and the final 2.5 day $3\sigma$ velocity covariance RSS is 0.596 mm/s. For the SRIF the final
2.5 day $3\sigma$ position covariance RSS 85.36 m and the final 2.5 day $3\sigma$ velocity covariance RSS is 0.595 mm/s. The 99th percentile of the norm of the position-state errors averages 25 m and 0.2 mm/s for velocity. The EKF is seen to have fewer outliers than the SRIF and has a denser peak in the error histogram. The error histogram is skewed right for both position and velocity. The DRO orbit state errors are slightly lower in the SS case than seen in the IOD case but on the same order of magnitude as the converged IOD solution. The filter has the worst state estimates in the $z$ and...
$v_z$ directions and the best estimates in the $x$ and $v_z$ directions. The results from the Monte Carlo simulations can be seen in Figures 6.22 and 6.23.

Figure 6.22: 99th percentile of position-state errors during the final 2.5 days of the 9.25 day SS Monte Carlo simulations for a DRO orbit. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.

Figure 6.23: 99th percentile of velocity-state errors during final 2.5 days of the 9.25 day SS Monte Carlo simulations for a DRO orbit. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.
6.7.3.2 \( L_1 \) Halo Orbit

For the \( L_1 \) case, the state errors stay bounded throughout the simulation by the \( 3\sigma \) covariance envelopes. Figures 6.24 and 6.25 show sample \( 3\sigma \) covariance envelopes and state errors over the 14.5 days of the simulation.

Figure 6.24: Evolution of the state covariance envelopes during a 9.25 day SS \( L_1 \) simulation using an EKF.

Figure 6.25: Evolution of the state covariance envelopes during a 9.25 day SS \( L_1 \) simulation using a SRIF.

From the Monte Carlo simulations, the final 2.5 day \( 3\sigma \) position covariance RSS for the EKF
is 120.66 m and the final 2.5 day 3\(\sigma\) velocity covariance RSS is 0.79 mm/s. For the SRIF the final 2.5 day 3\(\sigma\) position covariance RSS 120.54 m and the final 2.5 day 3\(\sigma\) velocity covariance RSS is 0.788 mm/s. The 99\(^{th}\) percentile of the norm of the position-state errors averages 30 m and 0.275 mm/s for velocity. The SRIF is seen to have fewer outliers then the EKF and has a denser peak in the error histogram. The error histogram is skewed right for both position and velocity. The L\(_1\) orbit state errors are lower in the SS case than seen in the IOD case indicating it can maintain the converged IOD solution for extended periods of time after convergence. The filter has the worst state estimates in the \(x\) and \(v_y\) directions and the best estimates in the \(y\) and \(v_x\) directions. The results from the Monte Carlo simulations can be seen in Figures 6.26 and 6.27.

![Images of error histograms](image)

(a) EKF  
(b) SRIF

Figure 6.26: 99\(^{th}\) percentile of position-state errors during final 2.5 days of the 9.25 day SS Monte Carlo simulations for a L\(_1\) orbit. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.

### 6.7.3.3 L\(_2\) Halo Orbit

For the L\(_2\) case, the state errors stay bounded throughout the simulation by the 3\(\sigma\) covariance envelopes. Figures 6.28 and 6.29 show sample 3\(\sigma\) covariance envelopes and state errors over the 14.5 days of the simulation.
Figure 6.27: 99\textsuperscript{th} percentile of velocity-state errors during final 2.5 days of the 9.25 day SS Monte Carlo simulations for a L\textsubscript{1} orbit. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.

Figure 6.28: Evolution of the state covariance envelopes during a 9.25 day SS L\textsubscript{2} simulation using an EKF.

From the Monte Carlo simulations, the final 2.5 day 3\sigma position covariance RSS for the EKF is 144.14 m and the final 2.5 day 3\sigma velocity covariance RSS is 0.564 mm/s. For the SRIF the final 2.5 day 3\sigma position covariance RSS 144.01 m and the final 2.5 day 3\sigma velocity covariance RSS is 0.553 mm/s. The 99\textsuperscript{th} percentile of the norm of the position-state errors averages 30 m and 0.19
Figure 6.29: Evolution of the state covariance envelopes during a 9.25 day SS L$_2$ simulation using a SRIF.

$m m / s$ for velocity. The EKF and SRIF are seen to have similar peak densities for the L$_2$ case, similar to the IOD case. The error histogram is skewed right for both position and velocity. The L$_2$ orbit state errors are lower in the SS case than seen in the IOD case indicating it can maintain the converged IOD solution for extended periods of time after convergence. The filter errors are consistent across each axis for position. The best velocity estimates are in the $v_x$ and $v_z$ directions and the worst estimates are in the $v_y$ directions. The results from the Monte Carlo simulations can be seen in Figures 6.30 and 6.31.

6.8 Conclusions

A satellite using HDNav can successfully perform IOD or maintain its state knowledge in lunar orbits. Using several Monte Carlo simulations, it has been shown that HDNav can provide a free, high performance alternative to traditional tracking methods in cis-lunar space. Both in stable (DRO) and unstable (L$_1$ and L$_2$) orbits, HDNav provides state estimates accurate to tens of meters and sub millimeter per sec. These simulations also show covariance envelopes with state estimates accurate to approximately 100 $m$ and 1 $mm/s$, which fully contain the state errors. Using high fidelity signal simulators, orbit propagators, and navigation filter suites, HDNav has been shown
Figure 6.30: 99th percentile of position-state errors during final 2.5 days of the 9.25 day SS Monte Carlo simulations for a L₂ orbit. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.

Figure 6.31: 99th percentile of velocity-state errors during final 2.5 days of the 9.25 day SS Monte Carlo simulations for a L₂ orbit. The bottom left figure shows the norm of the individual component true state errors. The remaining figures show the true state error in each of the individual component directions of the satellite. All errors are shown in the ECI coordinate frame.

to be effective for navigation at the moon. The ability of the filters to provide effective navigation solutions in highly non-linear environments, such as unstable lunar libration halo orbits, further
demonstrates the ability of HDNav. By using large Monte Carlo simulation runs, 20,070 for IOD and 10,035 for SS, the performance of the filters was shown to be robust to large initial deviations and able to converge to reasonable solutions.

The state estimates found by these simulations are on the same order of error accuracy that was achieved by the ARTEMIS mission. The ARTEMIS mission was able to achieve navigation solutions, in lunar libration halo orbits, good to better then 400 m and 2.4 mm/s during the mission. The HDTV signals used by HDNav are freely available signals which can be used as an alternative, supplement, or back-up to current navigation systems. These signals provide strong navigation solutions, beyond the GPS regime, out to cis-lunar space. They provide a significant number of signals to choose from spread around the world. This chapter demonstrates that HDNav can be a viable navigation system.
Chapter 7

Summary and Conclusions

The research presented in this thesis describes a method for obtaining navigation observables and performing satellite navigation using HDTV signals. This chapter will summarize this research, state conclusions and describe ways this research can be further developed through future work.

7.1 Summary of Contributions

A new method of performing orbit determination in lunar orbits was developed that uses HDTV signals as the source for navigation observables. This method of satellite navigation, known as HDNav, can potentially be used for autonomous navigation, or as an alternate, back-up or replacement system for missions. The transmission strength of HDTV signals, along with the signal structure of these signals, provide opportunities for timing to be extracted and used for satellite navigation in cis-lunar environments.

The feasibility of using these freely available terrestrial HDTV signals for orbit determination was evaluated. This was achieved through both orbital coverage analysis and link budget studies. For the coverage analysis, the percentage of orbit during which a HDTV signal was in view was analyzed. Both ATSC-only and full-world studies were performed for a variety of orbital regimes. Using Monte-Carlo-like studies of the orbital coverage, the optimal orbit locations for using HDNav, within a variety of orbital regimes (LEO, Molniya, and L1), was identified. Along with the coverage studies, link budget calculations were performed to fully evaluate HDNav's feasibility. These studies were used to determine if the HDTV signals were broadcast at high enough power levels to be
received and processed by an orbiting satellite. The link calculations were performed for both LEO orbital regimes and lunar $L_1$ orbits. The feasibility studies all showed that HDTV signals are a potential navigation data source for satellites on-orbit.

The ability to extract accurate timing from HDTV signals was studied. Using both simulated and real-data, signal-processing algorithms were tested to see what timing accuracy could be obtained. These signal-processing algorithms were tested both as post-processing techniques and in real-time using an FPGA. The timing seen in the signal was consistent with the expected timing found in the signal structure requirements. When the FPGA was used for the signal processing, the total data rate that the processor needs to handle was reduced by five orders of magnitude. The timing extracted from the signal was further tested using data collected in sub-orbital space by a high-altitude weather balloon.

Finally, a set of navigation Monte Carlo simulations was performed using the JANUS supercomputer at the University of Colorado - Boulder. These simulations used high fidelity models to assess the expected orbit determination accuracy that HDNav could provide a satellite in a variety of lunar orbits, including DROs and halo orbits about the lunar $L_1$ and $L_2$ points. Navigation simulations were performed to study both initial orbit determination cases as well as steady-state cases. These studies show that HDNav can potentially provide accurate navigation solutions to satellites using it as a primary navigation source, or in cases where a satellite loses their primary navigation source and uses HDNav as a back-up. A comparison of the orbit determination performance of both EKF and SRIF navigation filters was performed as well. It was shown that both filters provide navigation solutions with similar accuracy and computer resource draw. However, for use on-orbit the numerical stability provided by the SRIF makes it the recommended filter to be used.

7.2 Conclusions

This thesis has developed and demonstrated a potential navigation architecture which utilizes HDTV signals for the navigation observables. New navigation methods are of interest to the space community with a growing interest in crewed missions to both the lunar environment and beyond.
A reliable back-up navigation source is needed for these crewed missions to be viable options. This work presents an option for satellite navigation which can provide both resiliency and redundancy for satellites in the event other navigation sources become unavailable. By demonstrating an additional potential back-up navigation system, these future missions can have further redundancies and therefore be more feasible to fly. HDNav also offers a cost-effective navigation solution because HDTV signals are broadcast into the space environment continuously, free of cost.

7.3 Future Work

The research presented in this thesis presents the initial work for developing HDNav into a viable satellite navigation system. There are a number of areas where future work will help to further develop HDNav and improve its performance. This section addresses several ideas for how this research can be continued.

First, this work studied the use of ATSC signals only as the source of satellite navigation observables. Further study into the DVB-T and ISDB-T standards will open up opportunities for a satellite to utilize all possible HDTV transmissions for navigation. The DVB-T and ISDB-T standards both use orthogonal signals with strong timing information within the signal which could be exploited in a similar way to the ATSC signal components. Further study of these signal standards, along with performing experiments testing the strength of these signals, will go a long way in expanding HDNav’s reach. Extracting the timing found within these signals and testing these signals for navigation observables will be important for HDNav to be used to its full potential.

Further studies into the infrastructure of the transmission towers and local oscillators needs to be performed as well. These studies will help to highlight the variations between towers and the clock errors that a tower could experience if GPS is unavailable. These studies will also help to improve the resiliency of the system. These studies will also need to compare the performance and drifts seen in receiver hardware which would be tracking the HDTV signals. The hardware development and testing is vital to the final performance of HDNav on-orbit.

Another area where future work could be performed on the HDNav system is in running fur-
ther experiments for the ATSC signals. More aircraft flights studying multiple transmission towers
vertical gain patterns will help to show how consistent, or variable, every towers transmission pat-
terns are. Further high-altitude balloon tests need to be performed to test the real-time extraction
of navigation observables in sub-orbital regimes. Performing experiments which extract navigation
observables in real-time on the International Space Station (ISS) will further verify the ability of
these signals to be autonomously used in the space environment.

The navigation simulations performed can be run at even higher fidelity levels to further
define the limits of HDNav. These simulations could include features such as full gravity field
models for the Moon, as well as better model the effects of solar radiation pressure (SRP) and
other such features. Additionally instead of only modeling the signal errors from the transmitters,
realistic models of on-orbit hardware and their noise sources could be included in the models. These
would all increase the fidelity of the navigation simulations and further refine the results into what
would be seen by a real mission using HDNav.

Work needs to be performed to better define the media corrections that would be required
for the signals to be used on orbit. Ionospheric delays and other such media effects will need to be
accounted for in order for HDNav to work in the space environment. By tracking multiple signals
simultaneously broadcast at different frequencies throughout the orbit these media errors could be
solved for dynamically. Further studies need to be performed in order to fully characterize and
correct these media errors for the HDNav system.

Finally, studies need to be performed on isolating signals on-orbit whose frequency bands
overlap each other. When multiple ATSC signals are received on the same frequency, as would
be seen on orbit, identifying which towers each piece of timing information comes from becomes
important. Several different methods need to be studied in further detail to better solve this
problem. First, a satellite could utilize several high-gain antenna to point only at the transmission
towers of interest on the surface of the Earth. Another option is for the satellite to use a passive-
scan phase array to shape the beam-pattern and direct the antenna toward specific towers. Since
the signals will be separated in both time and power, on-orbit machine-learning or post-processing
could be used to group power returns and map the received signals over time to group them. This method would require long-term trackers in order to best collect the necessary information to separate the signals on orbit.

All of this future work will further establish the effectiveness of HDNav and its ability to provide orbit determination solutions to active satellites.
Bibliography


Appendix A

Kalman Filter

This appendix shows all of the math/steps for a Conventional and Extended Kalman Filter as described in Statistical Orbit Determination.

A.1 CKF

(1) Initialize filter at start time $t_0$ with the reference trajectory $X^*$, initial estimate of the state deviation $\hat{x}$, and the initial covariance $P$.

\[
X^*(t_{i-1}) = X_0^* \quad (A.1)
\]

\[
\hat{x}_{i-1} = \bar{x}_0 \quad (A.2)
\]

\[
P_{i-1} = \bar{P}_0 \quad (A.3)
\]

(2) Read observation, $Y$, at time $t_i$.

(3) Integrate reference trajectory and state transition matrix, $\Phi$, to $t_i$:

\[
\dot{X}^* = F(X^*(t), t) \quad (A.4)
\]
\[
\dot{\Phi}(t, t_{i-1}) = A(t)\Phi(t, t_{i-1}) \quad (A.5)
\]

The parameters of these equations include:

\[
A(t) = \left[ \frac{\partial F(X,t)}{\partial X} \right]^* \quad (A.6)
\]

(4) Perform time update. Calculate the time updated state deviation vector \( \bar{x} \), and the estimated covariance matrix, \( \bar{P} \):

\[
\bar{x}_i = \Phi(t_i, t_{i-1})\hat{x}_{i-1} \quad (A.7)
\]

\[
\bar{P}_i = \Phi(t_i, t_{i-1})P_{i-1}\Phi^T(t_i, t_{i-1}) \quad (A.8)
\]

(5) Calculate observation-state matrix, \( \tilde{H} \), Kalman gain, \( K \), and observation deviation vector, \( y \):

\[
\tilde{H}_i = \left[ \frac{\partial G(X,t_i)}{\partial X} \right]^* \quad (A.9)
\]

\[
K_i = \bar{P}_i\tilde{H}_i^T(\tilde{H}_i\bar{P}_i\tilde{H}_i^T + R_i)^{-1} \quad (A.10)
\]

\[
y_i = Y_i - G(X^*_i, t_i) \quad (A.11)
\]

The parameters of these equations include:

- \( G(X^*_i, t_i) \) is the computed measurement.

- \( Y_i \) is the current observation.
• $R_i$ is the expected Gaussian noise on the measurements.

(6) Perform measurement update. Calculate the current state deviation vector, $\hat{x}$, and time updated covariance matrix, $P$:

$$\hat{x}_i = \bar{x}_i + K_i[y_i - \bar{H}_i \bar{x}_i]$$  \hspace{1cm} (A.12)

$$P_i = (I - K_i \bar{H}_i) \bar{P}_i$$  \hspace{1cm} (A.13)

The parameters of these equations include:

• $\hat{x}_i$ is the estimated state deviation vector.

• $P_i$ is the estimated covariance matrix.

(7) Continue to the next observation, i.e., return to Step (2), or stop when all observations have been read.

A.2 EKF

An EKF has one difference from the CKF. The EKF updates the reference trajectory to the current best estimate of the satellite trajectory after every measurement update. This eliminates the need to propagate the state deviation vector.

A.3 Process Noise

For the navigation simulations performed in Chapter 6, process noise, in the form of state noise compensation (SNC), was used. By adding Equation (A.14) to the covariance matrix in step (4) from above SNC will be added to the filter.

$$P_{SNC} = \Gamma(t_i, t_{i-1}) Q \Gamma^T(t_i, t_{i-1})$$  \hspace{1cm} (A.14)
The parameters of these equations include:

\[
\Gamma(t_i, t_{i-1})Q\Gamma^T(t_i, t_{i-1}) = \Delta t^2 \begin{bmatrix}
\frac{\Delta t^2}{2} I \\
I
\end{bmatrix} \begin{bmatrix}
\sigma_x^2 \\
\sigma_y^2 \\
\sigma_z^2
\end{bmatrix} \begin{bmatrix}
\Delta t^2 I \\
I
\end{bmatrix}
\]

(A.15)

The parameters of Equation [A.15] include:

- \(Q\) is the process noise covariance matrix.
- \(\Gamma(t_i, t_{i-1})\) is the process noise state transition matrix.
- \(\sigma\) values are determined by the magnitude of the uncertainty of the acceleration acting on the system.
Appendix B

Square Root Information Filter

This appendix shows all of the math/steps for a Square Root Information Filter and an Extended Square Root Information Filter as described in Statistical Orbit Determination\textsuperscript{[1]} These filter definitions include the ability for the filter to add process noise and estimate parameters such as $C_R$, $C_D$ among others.\textsuperscript{[10]}

B.1 SRIF

(1) Initialize filter at start time $t_0$.

$R$ is initialized as the inverse of the Cholesky decomposition\textsuperscript{[1]} of the \textit{a priori} covariance matrix.

\begin{equation}
P_i = R_i^{-1}R_i^{-T}
\end{equation} \hspace{2cm} (B.1)

\begin{equation}
b = R\bar{x}_0
\end{equation} \hspace{2cm} (B.2)

(2) Read observation at time $t_i$.

(3) Integrate reference trajectory and state transition matrix to $t_i$:

\begin{equation}
\dot{X}^* = F(X^*(t), t)
\end{equation} \hspace{2cm} (B.3)
\[ \dot{\Phi}(t, t_{i-1}) = A(t)\Phi(t, t_{i-1}) \] (B.4)

The parameters of these equations include:

\[ A(t) = \left[ \frac{\partial F(X, t)}{\partial X} \right]^* \] (B.5)

(4) Perform time update:

\[ \bar{R}_i = R_{i-1}\Phi^{-1}(t_i, t_{i-1}) \] (B.6)

\[ \bar{b}_{i-1} = \bar{R}_{i-1}\bar{x}_{i-1} \] (B.7)

(5) Add process noise.

\[
\begin{bmatrix}
R_u & 0 & \bar{b}_{u_{i-1}} \\
-\bar{R}_i \Gamma(t_i, t_{i-1}) & \bar{R}_i & \bar{b}_{i-1} \\
-\bar{R}_i \Gamma(t_i, t_{i-1}) & \bar{R}_i & \bar{b}_{i-1}
\end{bmatrix}
= \begin{bmatrix}
\bar{R}_{u_i} & \bar{R}_{ux_i} & \bar{b}_{u_i} \\
0 & \bar{R}_i & \bar{b}_i
\end{bmatrix}
\] (B.8)

The parameters of Equation [B.8] include:

- \( \bar{T}_i \) indicates an orthogonal transformation of the matrix.
- \( R_u \) is the inverse of the Cholesky decomposition of the process noise covariance matrix, \( Q \).
- \( \Gamma(t_i, t_{i-1}) \) is the process noise state transition matrix.
- \( \bar{b}_{u_{i-1}} = R_u \bar{u}_{i-1} \), where \( \bar{u}_{i-1} \) is a zero mean process set to 0 at each update.

(6) Calculate observation-state matrix and observation deviation vector:

\[ \bar{H}_i = \left[ \frac{\partial G(X, t_i)}{\partial X} \right]^* \] (B.9)
\[ y_i = Y_i - G(X_i^*, t_i) \]  

(7) Perform measurement update:

\[
\begin{bmatrix}
\bar{T}_i & \bar{R}_i \\
H_i & y_i
\end{bmatrix}
= 
\begin{bmatrix}
\hat{R}_i & \hat{b}_i \\
0 & \hat{e}_i
\end{bmatrix}
\]

\[ \hat{x}_i = \hat{R}_i^{-1}\hat{b}_i \]  

The parameters of Equation B.8 include:

- \( \bar{T}_i \) indicates an orthogonal transformation \(^{107}\) of the matrix.

- \( H_i \) and \( y_i \) are whitened versions of \( \tilde{H}_i \) and \( y_i \) respectively. These are whitened by pre-multiplying by the inverse of the Cholesky decomposition of the measurement weighting matrix, \( R \).

(8) Continue to the next observation, i.e. return to Step (2), or stop when all observations have been read.

**B.2 ESRIF**

An ESRIF updates the reference trajectory to the current best estimate of the satellite trajectory after every measurement update. This eliminates the need to propagate the state deviation vector.

**B.3 Parameter Estimation**

For the navigation simulations performed in Chapter 6 the satellites’ coefficient of reflectivity was estimated along with the rest of the satellite states. By using Equation (B.13) for the state
propagation, parameters such as coefficient of reflectivity, clock errors, coefficient of drag, among others can be estimated.

\[
\begin{bmatrix}
  x_i \\
  c_i
\end{bmatrix} = \begin{bmatrix}
  \Phi_x & \Phi_c \\
  0 & I
\end{bmatrix} \begin{bmatrix}
  x_i \\
  c_{i-1}
\end{bmatrix}
\] (B.13)

The parameters of these equations can be defined as:

\[
X_i = \begin{bmatrix}
  x_i \\
  c_i
\end{bmatrix}
\] (B.14)

\[
\Phi(t_i, t_{i-1}) = \begin{bmatrix}
  \Phi_x & \Phi_c \\
  0 & I
\end{bmatrix}_i
\] (B.15)
Appendix C

Measurement Partials - Doppler

This appendix includes all of the partial derivatives used by the navigation filters in Chapter 6 for the Doppler measurement types. The Doppler measurement is defined by Equation (6.2) and is repeated here:

\[ t_{diff} = \frac{\dot{\rho} + \dot{\rho}_{bias}}{c + \dot{\rho} + \dot{\rho}_{bias}} t_{code} \]  

(C.1)

Where:

\[ \dot{\rho} = \frac{(\vec{r}_{sat} - \vec{r}_{trans}) \cdot (\vec{\dot{r}}_{sat} - \vec{\dot{r}}_{trans})}{|\vec{r}_{sat} - \vec{r}_{trans}|} \]  

(C.2)

The partial derivatives used for the navigation simulations from Chapter 6 are defined here.

\[ \frac{\partial t_{diff}}{\partial X_{sat}^i} = \frac{t_{code}}{(\rho_{bias} - \rho)} \left[ \frac{\dot{r}_i - \frac{\dot{\rho}}{\rho} r_i}{(c + \dot{\rho}_{bias} + \dot{\rho})} - \frac{(\dot{r}_i - \frac{\dot{\rho}}{\rho} r_i)(\dot{\rho}_{bias} + \dot{\rho})}{(c + \dot{\rho}_{bias} + \dot{\rho})^2} \right] \]  

(C.3)

\[ \frac{\partial t_{diff}}{\partial X_{sat}^i} = \frac{t_{code}}{(\rho_{bias} + \rho)} \left[ \frac{r_i}{(c + \dot{\rho}_{bias} + \dot{\rho})} - \frac{r_i(\dot{\rho}_{bias} + \dot{\rho})}{(c + \dot{\rho}_{bias} + \dot{\rho})^2} \right] \]  

(C.4)

\[ \frac{\partial t_{diff}}{\partial \rho_{bias}} = \frac{t_{code}}{(\rho_{bias} + \rho)(c + \dot{\rho}_{bias} + \dot{\rho})} \left[ \frac{\dot{\rho}(\dot{\rho}_{bias} + \dot{\rho})}{(c + \dot{\rho}_{bias} + \dot{\rho})} - \dot{\rho} \right] \]  

(C.5)

\[ \frac{\partial t_{diff}}{\partial \dot{\rho}_{bias}} = \frac{t_{code}}{(c + \dot{\rho}_{bias} + \dot{\rho})} \right] \left[ 1 - \frac{\dot{\rho}_{bias} + \dot{\rho}}{(c + \dot{\rho}_{bias} + \dot{\rho})} \right] \]  

(C.6)

The parameters of these equations include:
• $[X_{sat}^1 \ X_{sat}^2 \ X_{sat}^3] = [x_{sat} \ y_{sat} \ z_{sat}]$, and likewise for transmitter.

• $[\dot{X}_{sat}^1 \ \dot{X}_{sat}^2 \ \dot{X}_{sat}^3] = [\dot{x}_{sat} \ \dot{y}_{sat} \ \dot{z}_{sat}]$, and likewise for transmitter.

• $\vec{r} = \vec{X}_{sat} - \vec{X}_{trans}$

• $\rho$ and $\dot{\rho}$ are the range and range-rate to the satellite, defined by Equation (6.5) and (6.3) respectively.

• $t_{code} = 0.0242 \ sec$ for ATSC signals.

• $c$ is the speed of light.
Appendix D

Measurement Partials - DTO

This appendix includes all of the partial derivatives used by the navigation filters in Chapter 6 for the DTO measurement types. The DTO measurement is defined by Equation (6.7) and is repeated here:

\[
DTO = \frac{1}{c}[(\rho_{2up} + \rho_{2bias}) - (\rho_{1up} + \rho_{1bias})] 
\]

(D.1)

The partial derivatives used for the navigation simulations from Chapter 6 are defined here.

\[
\frac{\partial DTO}{\partial X_{sat}^i} = \frac{1}{c} \left[ \frac{r_i^2}{\rho_2} - \frac{r_i^1}{\rho_1} \right] 
\]

(D.2)

\[
\frac{\partial DTO}{\partial \dot{X}_{sat}^i} = 0 
\]

(D.3)

\[
\frac{\partial DTO}{\partial \rho_{1bias}} = -\frac{1}{c} 
\]

(D.4)

\[
\frac{\partial DTO}{\partial \rho_{2bias}} = \frac{1}{c} 
\]

(D.5)

The parameters of these equations include:

- \([X_{sat}^1 \; X_{sat}^2 \; X_{sat}^3] = [x_{sat} \; y_{sat} \; z_{sat}]\), and likewise for transmitter.

- \([\dot{X}_{sat}^1 \; \dot{X}_{sat}^2 \; \dot{X}_{sat}^3] = [\dot{x}_{sat} \; \dot{y}_{sat} \; \dot{z}_{sat}]\), and likewise for transmitter.
\( \vec{r}_i = \vec{X}_{sat} - \vec{X}_{trans} \) for the respective transmitter being tracked.

\( \rho_i \) and \( \dot{\rho}_i \) are the range and range-rate from the satellite to the tower being tracked, defined by Equation (6.5) and (6.3) respectively.

\( c \) is the speed of light.