Broadcast Positioning System (BPS) Using ATSC 3.0

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Abstract – This paper describes a novel Broadcast Positioning System (BPS), which can provide positioning, navigation, and timing (PNT) services using the ATSC 3.0 signal. The desired signal characteristics are first identified, and potential coverage in the contiguous United States is analyzed. Then, a mathematical model of a multilateration algorithm is formulated for the two-dimensional (X-Y plane) case and results of a pseudorange multilateration simulation are presented. Finally, some potential applications of BPS for resilient PNT are discussed.

Introduction and Summary

Television broadcast signals, which travel long distances and penetrate buildings, parking garages and other structures, can be used as a signal of opportunity for geolocation and timing. The ATSC 3.0 signal is especially well-suited for geolocation because of its robustness and data carrying capability. In this paper, a PNT system based on ATSC 3.0 is called a "Broadcast Positioning System" (BPS). The preamble part of the ATSC 3.0 signal can accurately report the corresponding time of a bootstrap transmission. Moreover, the precise location of the transmitting antenna can be sent as geolocation data within the channel. Therefore, if an ATSC 3.0 receiver can estimate the time of arrival (TOA) of the received bootstrap signal, in addition to decoding the preamble and the data-carrying physical layer pipe (PLP), the receiver can compute the tower-to-receiver pseudorange.[1] However, if the receiver receives signals from at least three geographically-separated transmission antennas and thus calculates at least three pseudoranges, the receiver can compute its location using multilateration algorithms.

Section 1 identifies the data fields that need to be populated in the transmitted ATSC 3.0 signal. This section also discusses the transmission side requirements and implementation schemes. Section 2 provides an illustrative coverage analysis of the proposed ATSC 3.0 BPS waveform within the contiguous United States. Section 3 describes a multilateration technique that uses an iterative approach to find a weighted least-squares position solution. Section 4 shows an implementation of the multilateration technique and simulation results of the same. Section 5 proposes neighbor signal measurement, which increases yield and resiliency. Section 6 discusses some use cases and adoption strategies.

Section 1: Signal of Interest

The simplest way to implement the BPS system is to send the location of the transmitter as data in a robust PLP in addition to accurately populating the `L1-Basic` and `L1-Detail` signaling fields of the

[1] Called a "pseudorange" instead of "range" because the apparent range includes distance errors due to unknown receiver clock bias.

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preamble [1]. In particular, the L1B_time_info_flag field needs to be set to 11b, and the L1D_time_sec, L1D_time_msec, L1D_time_usec and L1D_time_nsec fields need to be populated with accurate values.

Estimating Bootstrap Transmission Time

The preamble, which describes the transmission time of the bootstrap signal, is formed before the bootstrap in the logical flow. After the preamble is formed, the signal passes through a number of processes such as frequency interleaving, pilot insertion, inverse fast Fourier transform (IFFT), peak-to-average power ratio reduction, and bootstrap generation. The additional logical blocks introduce varying levels of hardware and software delays.

After the signal passes through the digital-to-analog converter (DAC) and enters the analog domain, the signal experiences additional delay in analog devices such as filters, amplifiers, waveguides and transmission lines before it is radiated by the antenna. The data fields L1D_time_sec, L1D_time_msec, L1D_time_usec and L1D_time_nsec, however, need to be populated with the emission time of the of the rising edge of the first sample of the first symbol of the bootstrap. Therefore, the digital and analog delays need to be compensated for during preamble generation.

A reliable way of compensating for the various delays in the transmission chain is to continuously measure it and adjust for it as shown in Figure 1. A tracking loop with a loop filter is recommended.

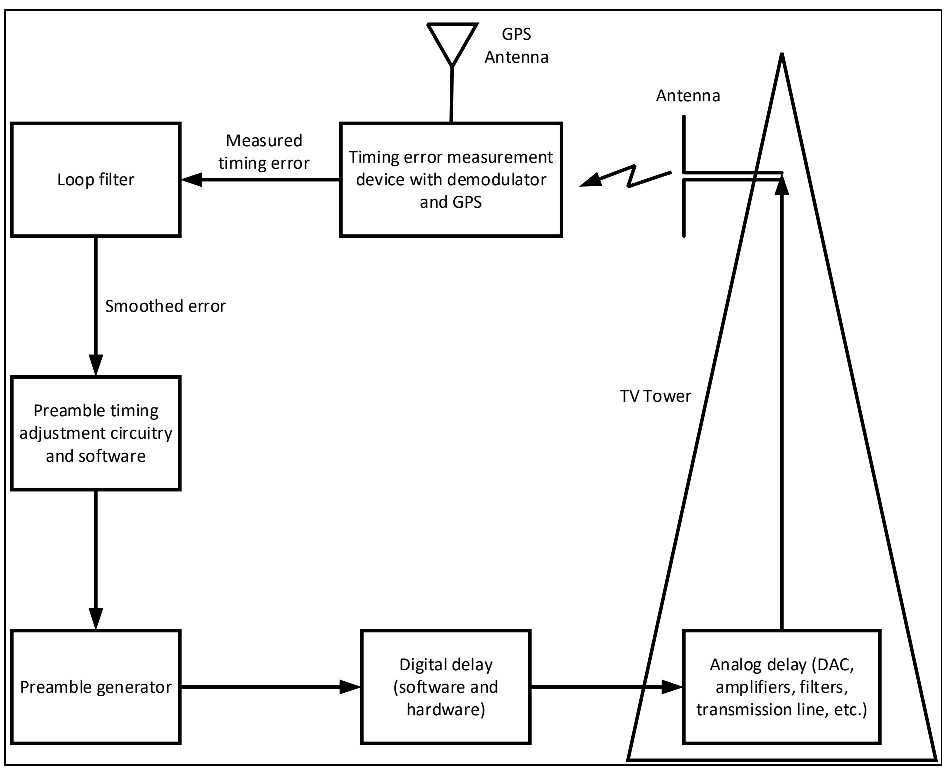

FIGURE 1: TIMING ADJUSTMENT TRACKING LOOP.

Section 2: Estimate of BPS Coverage in the Contiguous United States

Coverage Definition

According to [2], the most robust PLP operates at -5.72 dB signal to noise ratio (SNR) in a Rayleigh fading channel. Simulations shared by the proponents during ATSC 3.0 standards development showed that the bootstrap and preamble can be decoded at about -12 dB and -9 dB SNR, respectively. Therefore, the data PLP carrying the tower location information is the weakest link, requiring the highest signal level. It is expected that BPS will utilize a PLP having robust characteristics in order to provide usable coverage at great distances from the transmitter site as well as providing coverage deep indoors and in other challenging environments. We have used -5 dB as the BPS system threshold. This threshold is about 20 dB below what is typically assumed for DTV reception. Other relevant planning factors used to define BPS coverage are tabulated in Table 1.

Parameter	Value	Unit
System Bandwidth	6	MHz
Thermal Noise (kTB)	-106.2	dBm
Frequency of Operation	539	MHz
Antenna Gain	0	dBi
Antenna Factor	-129.6	dBm-dBµV/m
Noise Figure	6	dB
Required Field Strength	**24.4**	**dBµV/m**
RX Antenna height, AGL	1.5	m
Location, Time Variability	50%, 50%	–

TABLE 1: PLANNING FACTOR VALUES USED TO DEFINE BPS COVERAGE.

Station Selection

While timing information and real-time kinematic (RTK) corrections might be adequately conveyed from a single broadcast station, position determination requires a minimum of three broadcast stations. Further, the transmitting antennas for each of the three stations must be in a different physical location in order to produce an unambiguous solution (position) by hyperbolic navigation. Closely sited or even collocated stations might also be used to “overdetermine” a position solution with reduced uncertainty, but at least three widely spaced stations are needed to unambiguously resolve a two-dimensional position in the simplest case. A larger number of stations, geographically dispersed, will also reduce the uncertainty of the position solution.

A minimum physical spacing requirement of one kilometer or greater between the stations is offered as being sufficient for useful position determination. This distance is equivalent to a free-space propagation time of about 3.3 µsec, which should be adequate for reasonable and useful accuracy for the system. This minimum spacing requirement necessitates selecting one station from each collocation (or near collocation) transmitter site for analysis. As an example, while One World Trade Center in New York City has 16 television stations operating from it, only the one full-power UHF station having the largest coverage area was used for this analysis. The other stations at that site were not included in the analysis.

U.S. television stations may transmit on low-VHF channels (below 88 MHz), high-VHF channels (between 174 and 216 MHz) and UHF channels (above 470 MHz). The authors believe that initial implementations of BPS may rely on UHF signals only. This is because user equipment is likely to have limited bandwidth and the majority of TV broadcast stations are on UHF channels. Therefore, VHF stations are not considered in this analysis.

There are a large number of low-power television (LPTV) stations (including TV translator stations) that serve areas of the U.S. that are unserved or poorly served by full-power stations. LPTV stations are expected not to widely deploy BPS initially for several reasons. First, the cost of adding BPS at the transmission side is expected to be similar for both full-power and low-power stations making the economics more challenging. Second, most low-power stations rebroadcast one or more primary stations making implementation more challenging. Finally, the technological evolution of low-power stations typically lags that of full-power stations. Therefore, low-power stations are not considered in this report.

BPS Coverage Determination

Because of its familiarity to the broadcast industry and because reference software has been published by the FCC, [3] the Irregular Terrain Model (ITM, version 1.2.2) was utilized in its point-to-point mode to predict coverage on a uniform grid covering the Contiguous United States. A summary of the ITM, including descriptions of some of its features and peculiarities, is given in Paul, *et al*. [4] The software implementation of ITM used was the FCC's TVStudy, version 2.2.5, but included a number of non-standard parameter settings as shown in Appendix A. In particular, the software was configured to predict field strength at 1.5 meters above ground, coverage was defined as 24.4 dBμV/m or greater irrespective of the UHF channel involved and no consideration was given to undesired stations (*i.e.*, co-channel and adjacent-channel interference was ignored).

Results

The map of Figure 2 shows the predicted aggregate coverage of BPS of all non-collocated, full-power UHF television stations in the contiguous U.S. (CONUS). The total land area of CONUS is about 7.7 million square kilometers, while the predicted aggregate BPS coverage is about 6.5 million square kilometers [5]. That is, about 84% of CONUS would be covered by at least one BPS signal.

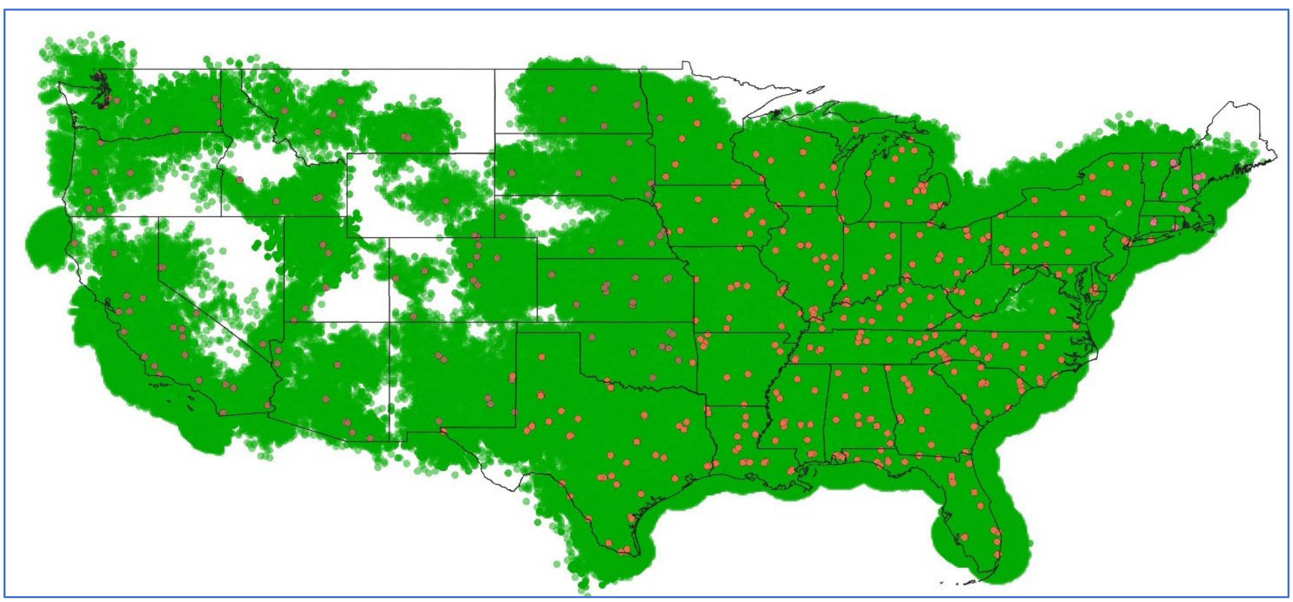

FIGURE 2: CONUS AREAS COVERED BY AT LEAST ONE FULL-POWER UHF TV STATION WITH PLANNING FACTOR VALUES GIVEN IN TABLE 1.

As discussed above, at least three BPS signals from non-collocated stations must be recovered to produce a position solution, with more signals providing improved accuracy. With that in mind, each coverage grid point was examined to determine how many BPS stations were predicted to provide an adequate signal. Table 2 provides the number of cells covered by 2, 3, 4 and more unique BPS signals and the fraction of CONUS that would be covered. Over one-half of the land area of CONUS is predicted to be covered by three or more BPS signals. Of course, the addition of VHF stations and low-power stations would substantially increase these coverage estimates.

# Stations	Cell Count	Fraction of CONUS
≥10	4289	6%
≥9	6272	8%
≥8	8887	12%
≥7	12618	16%
≥6	17370	23%
≥5	23360	30%
≥4	30688	40%
≥3	40083	52%
≥2	50773	66%
≥1	64748	84%
Total CONUS Area	77000	

TABLE 2. PREDICTED COVERAGE AREA (CONUS) BY 1, 2, 3, AND MORE NON-COLLOCATED, FULL-POWER UHF-TV STATIONS RUNNING BPS.

Section 3: Multilateration Technique

We start formulating the multilateration mathematical model with the assumption that the location of the receiver is on or near the surface of the earth. Additionally, the surface of the earth within the coverage area is assumed to be flat, and latitude and longitude values of the service area are converted to cartesian coordinates without loss of generality as the cartesian coordinates can be converted back to latitude and longitude values after the multilateration computation [6][8][9].

Let us assume that (x_1,y_1), (x_2,y_2), (x_3,y_3) are the known tower locations and (x,y) is the receiver location that needs to be estimated. Let t be the receiver clock offset compared to the reference clock that the towers are using. If c is the speed of light, the tower-to-receiver pseudoranges r1, r2, and r3 can be expressed as follows:

$$r_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} + ct = f_1(x, y, t) \quad (1)$$

$$r_2 = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} + ct = f_2(x, y, t) \quad (2)$$

$$r_3 = \sqrt{(x_3 - x)^2 + (y_3 - y)^2} + ct = f_3(x, y, t) \quad (3)$$

The variables x, y and t in (1) - (3) can be determined using well-known techniques described in [7] and [8]. The following iterative technique is based on [8].

Let $(\hat{x},\hat{y})$ be the estimated location of the receiver and $\hat{t}$ be the estimated clock offset. Substituting these values into (1) – (3) provides the following:

$$\hat{r}_1 = \sqrt{(x_1 - \hat{x})^2 + (y_1 - \hat{y})^2} + c\hat{t} = f_1(\hat{x}, \hat{y}, \hat{t}) \quad (4)$$

$$\hat{r}_2 = \sqrt{(x_2 - \hat{x})^2 + (y_2 - \hat{y})^2} + c\hat{t} = f_2(\hat{x}, \hat{y}, \hat{t}) \tag{5}$$

$$\hat{r}_3 = \sqrt{(x_3 - \hat{x})^2 + (y_3 - \hat{y})^2} + c\hat{t} = f_3(\hat{x}, \hat{y}, \hat{t}) \tag{6}$$

where $\hat{r}_1$, $\hat{r}_2$, and $\hat{r}_3$ are the estimated pseudoranges associated with the location ($\hat{x}$,$\hat{y}$) and clock offset $\hat{t}$.

Let us define the true receiver location and time offset in terms of estimated values and difference as shown below:

$$x = \hat{x} + \Delta x \tag{7}$$

$$y = \hat{y} + \Delta y \tag{8}$$

$$t = \hat{t} + \Delta t \tag{9}$$

Now let us linearize (1). First, we substitute (7) into (1) and obtain the following:

$$r_1 = f_1(x, y, t) = f_1(\hat{x} + \Delta x, \hat{y} + \Delta y, \hat{t} + \Delta t) \tag{10}$$

We then expand (10) keeping only the first-order derivative terms. This approximation is valid when the estimated values are in the vicinity of the true value.

$$r_1 \approx f_1(\hat{x}, \hat{y}, \hat{t}) + \frac{\partial f_1(\hat{x}, \hat{y}, \hat{t})}{\partial \hat{x}} \Delta x + \frac{\partial f_1(\hat{x}, \hat{y}, \hat{t})}{\partial \hat{y}} \Delta y + \frac{\partial f_1(\hat{x}, \hat{y}, \hat{t})}{\partial \hat{t}} \Delta t \tag{11}$$

Substituting (4) into (11) and evaluating the partial derivatives provides the following:

$$r_1 = \hat{r}_1 - \frac{(x_1 - \hat{x})}{\sqrt{(x_1 - \hat{x})^2 + (y_1 - \hat{y})^2}} \Delta x - \frac{(y_1 - \hat{y})}{\sqrt{(x_1 - \hat{x})^2 + (y_1 - \hat{y})^2}} \Delta y + c\Delta t \tag{12}$$

$$\hat{r}_1 - r_1 = \frac{(x_1 - \hat{x})}{\sqrt{(x_1 - \hat{x})^2 + (y_1 - \hat{y})^2}} \Delta x + \frac{(y_1 - \hat{y})}{\sqrt{(x_1 - \hat{x})^2 + (y_1 - \hat{y})^2}} \Delta y - c\Delta t \tag{13}$$

Let us define Δr_1 as follows:

$$\Delta r_1 = \hat{r}_1 - r_1 \tag{14}$$

Equations (13) and (14) provide the following linearized equation:

$$\Delta r_1 = \frac{(x_1 - \hat{x})}{\sqrt{(x_1 - \hat{x})^2 + (y_1 - \hat{y})^2}} \Delta x + \frac{(y_1 - \hat{y})}{\sqrt{(x_1 - \hat{x})^2 + (y_1 - \hat{y})^2}} \Delta y - c\Delta t \tag{15}$$

Similarly, we can derive the linearized equations for the other two pseudoranges.

$$\Delta r_2 = \frac{(x_2 - \hat{x})}{\sqrt{(x_2 - \hat{x})^2 + (y_2 - \hat{y})^2}} \Delta x + \frac{(y_2 - \hat{y})}{\sqrt{(x_2 - \hat{x})^2 + (y_2 - \hat{y})^2}} \Delta y - c\Delta t \tag{16}$$

$$\Delta r_3 = \frac{(x - \hat{x})}{\sqrt{(x_3 - \hat{x})^2 + (y_3 - \hat{y})^2}} \Delta x + \frac{(y - \hat{y})}{\sqrt{(x_3 - \hat{x})^2 + (y_3 - \hat{y})^2}} \Delta y - c\Delta t \tag{17}$$

Representing (15) – (17) in matrix form, we obtain:

$$\boldsymbol{\Delta r} = \begin{bmatrix} \Delta r_1 \\ \Delta r_2 \\ \Delta r_3 \end{bmatrix} \tag{18}$$

$$\boldsymbol{H} = \begin{bmatrix} \frac{(x_1-\hat{x})}{\sqrt{(x_1-\hat{x})^2+(y_1-\hat{y})^2}} & \frac{(y_1-\hat{y})}{\sqrt{(x_1-\hat{x})^2+(y_1-\hat{y})^2}} & 1 \\ \frac{(x_2-\hat{x})}{\sqrt{(x_2-\hat{x})^2+(y_2-\hat{y})^2}} & \frac{(y_2-\hat{y})}{\sqrt{(x_2-\hat{x})^2+(y_2-\hat{y})^2}} & 1 \\ \frac{(x-\hat{x})}{\sqrt{(x_3-\hat{x})^2+(y_3-\hat{y})^2}} & \frac{(y-\hat{y})}{\sqrt{(x_3-\hat{x})^2+(y_3-\hat{y})^2}} & 1 \end{bmatrix} \tag{19}$$

$$\boldsymbol{\Delta x} = \begin{bmatrix} \Delta x \\ \Delta y \\ -c\Delta t \end{bmatrix} \tag{20}$$

Therefore,

$$\boldsymbol{\Delta r} = \boldsymbol{H}\boldsymbol{\Delta x} \tag{21}$$

or equivalently:

$$\boldsymbol{\Delta x} = \boldsymbol{H}^{-1}\boldsymbol{\Delta r} \tag{22}$$

If there are more than three pseudoranges, the matrix **H** will have more than three rows, and the least-square solution will be:

$$\boldsymbol{\Delta x} = (\boldsymbol{H}^T\boldsymbol{H})^{-1}\boldsymbol{H}^T\boldsymbol{\Delta r} \tag{23}$$

It is possible to assign different weights to each pseudorange during the multilateration computation. These weights can be assigned based on signal to noise ratio (SNR), multipath delay spread, or measurement variance. If w_1, w_2, …, w_n are the weights assigned to n pseudoranges, the general weighted least square (WLS) solution will be as follows:

$$\boldsymbol{\Delta x} = (\boldsymbol{H}^T\boldsymbol{W}\boldsymbol{H})^{-1}\boldsymbol{H}^T\boldsymbol{W}\boldsymbol{\Delta r} \tag{24}$$

where

$$\boldsymbol{W} = \begin{bmatrix} w_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & w_n \end{bmatrix} \tag{25}$$

The unknown receiver location (x,y) can then be estimated applying (22), (23), or (24) iteratively. If the initial estimate is close, the next estimate is usually better than the initial estimate. After a few iterations, the estimates should converge. The following is a breakdown of the steps:

- **Step 1**: Choose the initial estimate ($\hat{x}$,$\hat{y}$) somewhere near the likely position. The centroid of the tower locations could be a reasonable guess. Set the clock offset $\hat{t}$ to 0 (or another reasonable value).
- **Step 2**: Compute **Δr** using (4) – (6), (14) and (18).
- **Step 3**: Compute **Δx** using (22), (23) or (24) as appropriate.
- **Step 4**: Compute the location using (7) – (9).

- **Step 5**: If **Δx** is below a chosen threshold, *e.g.*, 1 meter, assume that the newly computed (x,y) values are the computed location. Stop and exit the loop.
- **Step 6**: If **Δx** is above the threshold, go to Step 1 and assume that the newly computed (x,y) values are the newly estimated values $(\hat{x},\hat{y})$. Execute the subsequent steps until **Δx** converges or until maximum number of iterations has been reached.

The multilateration computation loop may sometimes diverge depending on the deviation of the initial estimates from the true position, tower geometry and the level of inaccuracy in pseudorange values. The divergence can sometimes be mitigated by limiting the values of Δx and Δy in the **Δx** matrix. For example, if the magnitude of the vector Δx+jΔy is greater than some threshold, say 50 km, then the values Δx and Δy can be scaled so that the direction of the vector is preserved but the magnitude is equal to the threshold.

Section 4: Simulation Results

A simulation was performed to test the basic assumptions of our proposition. We chose four towers each with antennas installed at 200 meters above the reference (X-Y) plane. The tower locations were (50000, 0), (0, 50000), (-50000, 0), and (0, -50000) meters on that plane. For each test point within the area of interest, we added random TOA estimation errors, random multipath errors and a random clock offset to simulate variability in the pseudoranges. We then applied the WLS algorithm with equal weights and a maximum convergence step size of 10000 m.

TOA Estimation Error

The Cramér-Rao bound (CRB) provides a lower bound of the TOA estimation variance. For a signal with rectangular spectrum, the TOA standard deviation is expressed as

$$\sigma = \frac{0.55}{B}\frac{1}{\sqrt{BT\gamma}} \tag{26}$$

where σ is that minimum standard deviation of TOA estimation error, B is the bandwidth of the signal, T is the signal integration time, and γ is the input SNR [10]. For the ATSC 3.0 bootstrap signal, B = 4.5 MHz and T = 1.5 ms. Since we have assumed that the minimum SNR for the data PLP is -5 dB, we set γ = -5 dB. Using (26), we obtain standard deviation, σ = 2.65 ns (or equivalently 0.79 m in distance).

The duration of bootstrap samples is 162.76 ns, which is 48.8 m in distance. Typical TOA implementations can achieve average accuracy of better than 5% of the sample duration, which is about 2.44 m in this case. For the simulation, we have modelled the TOA estimation error as uniform distribution between -5 m to +5 m. Standard deviation of such a distribution is 10 $10/\sqrt{12}$ = 2.89 m, which is well above the CRB.

Multipath Error

Television channels can exhibit large delay spreads. However, the earliest detected TOA will be used for multilateration. We have assumed that the earliest detected multipath has a range error that is uniformly distributed between 0 and 100 m.

Clock Offset

An ATSC 3.0 receiver can lock its internal clock to a TV station's clock via the timing information transmitted on `L1-Basic` and `L1-Detail` signaling fields of the preamble. Therefore, it can be assumed that the clock offset will be of the order of the distance to the tower the receiver can receive signal form. For the test points in our simulation, we have used the distance to the nearest tower as clock offset.

Simulator Output

A typical output from a run of the simulator is shown below.

```
TOA estimation error:  4.1 m, -3.2 m, -2.4 m, -3.5 m,
multipath error:      13.6 m, 86.9 m, 58.0 m, 55.0 m,
clock offset:  25495.9 m
true (x,y,t):       x = -25000.0 m, y =  -5000.0 m, t =  25495.9 m
estimated (x,y,t): x = -24989.9 m, y =  -5015.7 m, t =  25549.6 m
estimation error:  x =    -10.1 m, y =     15.7 m, t =    -53.7 m
estimation error (distance):       18.7 m
```

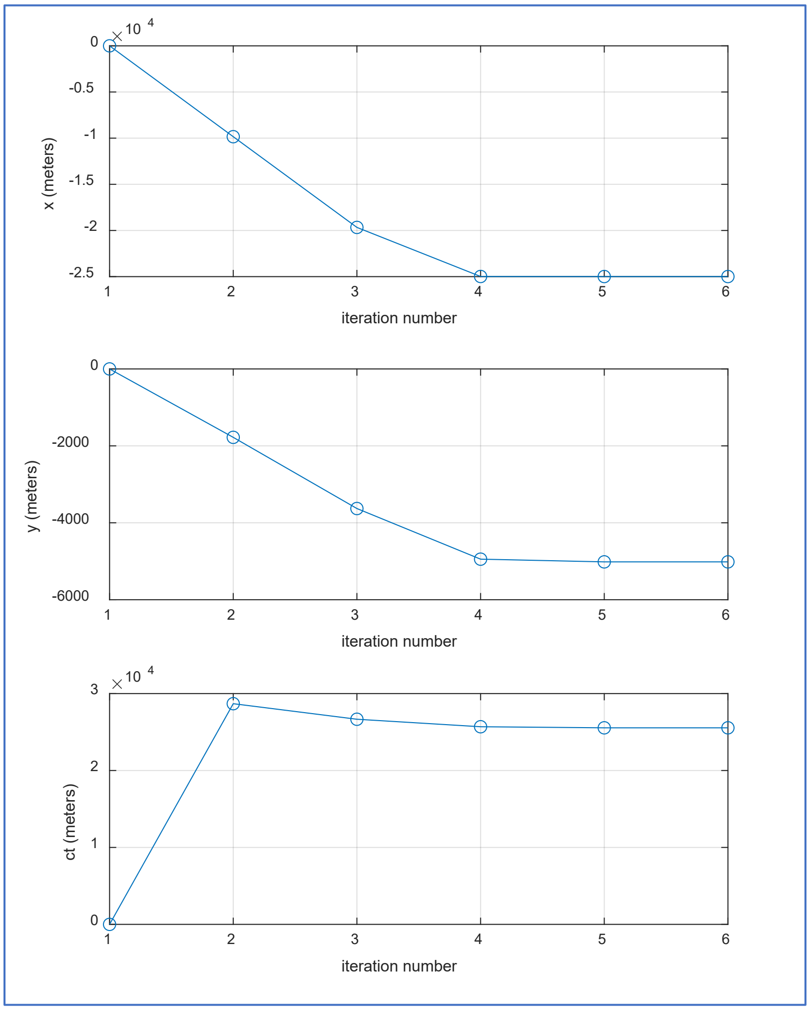

FIGURE 3: CONVERGENCE OF POSITION AND CLOCK OFFSET WITH ITERATION.

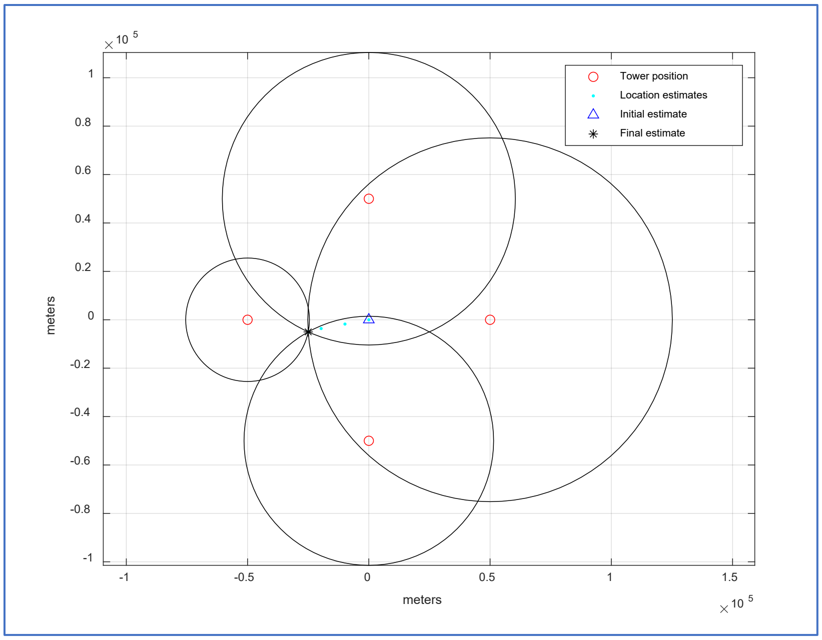

FIGURE 4: CONVERGED POSITION ESTIMATE.

The simulation was run for 100,000 random points in the vicinity of the coverage area. Although the test points were randomly selected, they were bounded by a square with vertices at (45000, 45000), (-45000, 45000), (-45000, -45000), (45000, -45000). The multilateration technique works beyond this imaginary square albeit with slightly degraded performance. We chose the boundary values merely for ease of simulation. Each test point had four random TOA estimation errors, four random unresolved multipath errors, and a clock offset equivalent to the distance to the nearest tower. The tower position and simulation test points are shown in Figure 5.

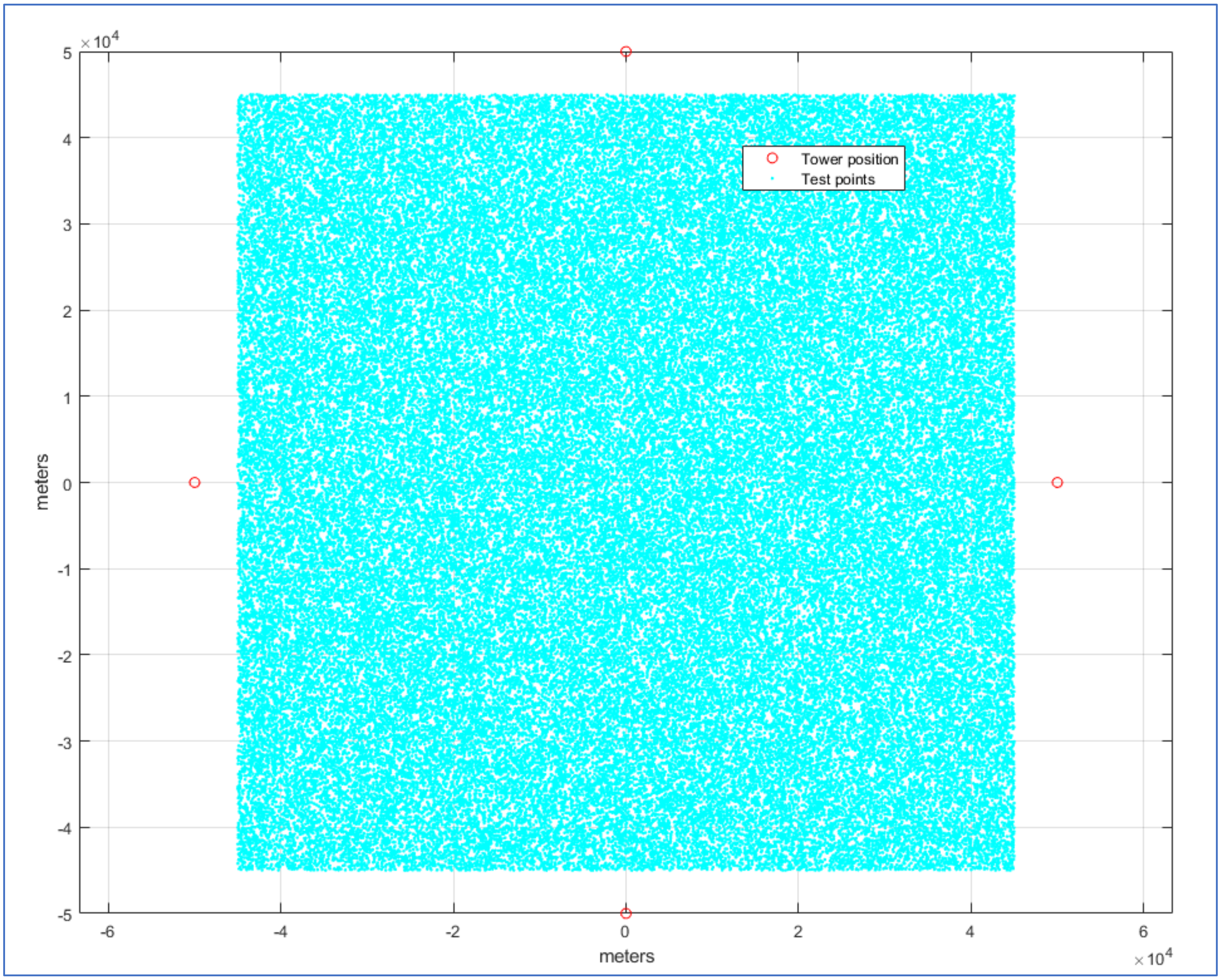

FIGURE 5: SIMULATION TEST POINTS RELATIVE TO TOWER POSITION.

The position- and clock-offset estimation errors for the above mentioned 100,000 points are shown in Figure 6. It was observed that the probability density functions (pdf) of the estimation errors Δx, Δy and Δt of (7), (8) and (9) were bell-shaped, whereas the pdf of $\sqrt{\Delta x^2 + \Delta y^2}$ had the general shape of a chi-distribution with 2 degrees of freedom. This is an expected outcome. Position accuracy for the 100,000 test points had a mean error of 35 m with a standard deviation of 22 m. Clock offset estimation error had a mean of -50.6 m with a standard deviation of 25 m. The negative bias in clock offset is due to unresolved multipath.

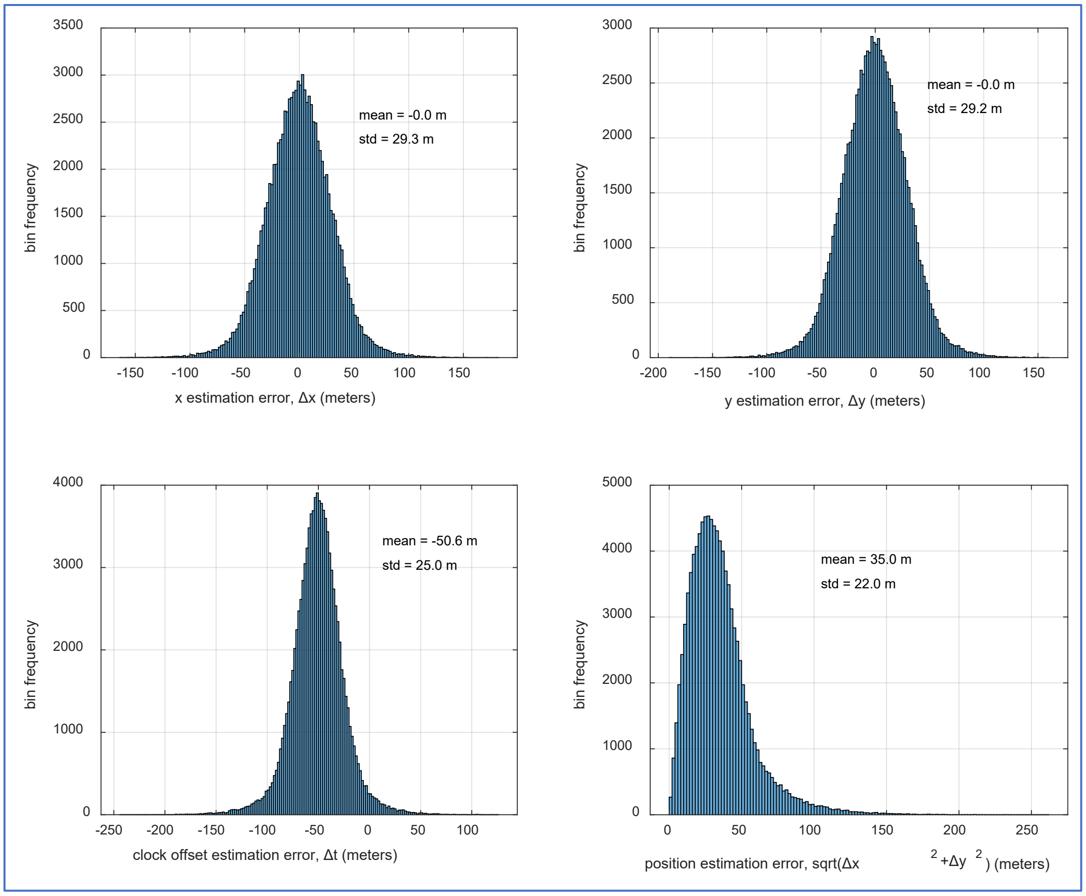

FIGURE 6: HISTOGRAMS OF POSITION AND TIME ESTIMATION ERRORS.

Section 5: Increasing Yield and Resiliency Using Neighbor Broadcast Station Measurements

The -5 dB SNR signal coverage analysis in Section 2 was based on the assumption that the data PLPs that would carry the tower location information for each individual tower were successfully decoded at the receiver. However, only -9 dB SNR is required to decode the preamble signal that carries the timestamps. This provides an opportunity to extend the BPS service coverage area by 4 dB if the tower locations associated with preamble timestamps are made available to the receiver by other means. One way to implement this is to transmit all of the neighboring tower locations from all the TV towers. In this case, an ATSC 3.0 receiver needs only one -5 dB (or better) signal from one tower while -9 dB (or better) signals would suffice for rest of the towers.

The above concept can be further extended if all the neighboring towers measure each other's emission times and report the neighbor measurements in the data PLP. That way, if an ATSC 3.0 receiver decodes just one channel at -5 dB SNR but estimates bootstrap TOAs at -12 dB SNR for the rest of the neighboring towers, the receiver can determine the emission timestamps as well as the locations of the towers whose bootstrap TOAs were detected but whose preambles were not successfully decoded. Such an implementation would extend the coverage by reducing the SNR required by about 7 dB.

Another benefit of sending data on neighbor stations is improved resiliency against spoofing. If a TV station is compromised and transmits misleading BPS information, the receiver can identify the discrepancy and take appropriate measures. While we expect that most TV stations implementing BPS will lock their timing reference to satellite-based GPS, high-accuracy local references (such as rubidium standards) might also be used. A secondary fallback reference would be useful to detect spoofing of GPS satellite signals as well as providing additional confidence that BPS-based PNT data are reliable.

The generic multilateration technique described in Section 3 is often enhanced and customized in real systems. Practical implementations may use additional information and optimize the location estimation algorithms. Antenna height, radiation pattern, terrain information, and transmit power can be useful, in addition to timing related information, for location estimation. For example, the initial location estimate, which impacts the convergence behavior of the WLS algorithm, can be improved using the above-mentioned information. The same pieces of information can also be used to increase resiliency against spoofing.

Finally, better accuracy can be achieved by sending the emission time measurement errors of previous frames. Even though the discrepancy between the actual transmission time and the timestamp reported in the preamble can be minimized by adopting the compensation technique shown in Figure 1, there will always be some residual error described as *Measured timing error* in the same figure. If the measurement errors of the previously transmitted bootstrap signals are reported to the receiver, the receiver can apply those corrections to the past location estimates. For example, assume a receiver estimates its location with 50 m uncertainty because of inaccurate time-stamping. Three seconds later, when the receiver receives the *Measured timing error* values for the same set of pseudorange measurements, the receiver can apply those corrections and recompute the locations with just 20 m estimation error. In this case, the receiver calculated one position estimate immediately but can optionally get a better estimate a few seconds later.

Based on the above discussion, we recommend that each tower transmits the following information in the data pipe:

- Transmit antenna ID (a unique ID to distinguish the antenna);
- Transmit antenna position (x, y. z), or latitude, longitude, and elevation;
- Transmit antenna radiated power;
- Transmit antenna radiation pattern (and/or average coverage radius);
- Neighbor station antenna IDs;
- Neighbor station channels (frequencies);
- Neighbor antenna positions (x, y. z), or latitudes, longitudes, and elevations;
- Neighbor antenna radiated power levels;
- Neighbor antenna radiation patterns;
- Timing offset of the neighbor bootstrap signals relative to the self bootstrap signal (this offset could either be the one observed at the self (transmitter) site or can be compensated for the distance travelled);
- Current number of leap seconds expressed as TAI – UTC (this value is desired so that decoding of A/331 video service messages are not required for location computation);
- Reported bootstrap transmission time of the previous frames (for both self and neighbors);
- Measured time-stamp reporting error of the previous frames (for both self and neighbors).

Section 6: Use Cases and Potential Opportunities

To better understand the potential opportunities, the benefits of BPS that make it a desirable solution are articulated below. Television broadcast signals:

- are transmitted from stationary towers with known coordinates;

- are often from tall towers, some as high as 2,000 feet;
- are high power signals, with many stations operating at one megawatt (MW) Effective Radiated Power (ERP);
- are wide-band and operate across a wide range of frequencies;
- have excellent coverage, particularly in densely populated areas;
- can penetrate buildings and other structures;
- are operated from hardened facilities designed to stay on the air during emergencies.

There are numerous well-known and established PNT applications in use today. Route guidance is probably the best known as such systems are included in our cars, mobile phones, or purpose-built moving map devices. In the most basic sense, BPS could provide an addition to GPS resiliency and augmentation in such applications. In a more integrated solution, BPS signals could be incorporated in systems that monitor other frequencies to provide greater accuracy to those existing systems. This is akin to what the Federal Aviation Administration (FAA) did with the deployment of Automatic Dependent Surveillance – Broadcast (ADS-B) to general aviation to give air traffic controllers the ability to better manage traffic in high density areas.

From a cybersecurity perspective, having a highly reliable alternative to GPS is very desirable. GPS spoofing is a known issue and one that many experts have cited as an important threat vector in the decade ahead. Receivers could layer on BPS to existing GPS-centric systems as a means of spoof detection. Detection of a disagreement between BPS and GPS timing signals could trigger an alarm that could warn local GPS users not to rely on position information. While BPS-equipped transmitting facilities are envisioned to use GPS timing as a reference, they could also include secondary timing references on-site that would operate independently of satellite-based GPS for a period while GPS signals are compromised.

BPS could play an important role for first responders. The ability to receive PNT signals indoors could help firefighters, police, and emergency medical technicians rapidly locate people in distress quicker.

If we look at the traditional broadcast business, BPS-outfitted televisions and receivers could enable targeted content even on devices that aren't connected to the Internet. A Next Gen TV could compute its location solely based on the ATSC 3.0 signals it receives. This could allow geotargeting of broadcast services. An example of this is sending weather alerts only to TV sets that are within an area of interest. This could also be used for better targeted advertising and help to match the capabilities that exist on internet connected televisions.

Conclusion

BPS provides another signal of opportunity for many different PNT solutions, including independent determination of position, improved operation indoors and other challenging environments, augmentation of satellite-based systems for improved accuracy, and resilience to spoofing and denial. Given the existing nationwide infrastructure of broadcast television stations, BPS can be deployed quickly and at a relatively low incremental cost, making it an attractive option for consideration. Broadcasters that choose to deploy BPS would bolster their importance as components of critical infrastructure and could potentially realize new sources of revenue.

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Appendix A – TVStudy Parameters Used for Coverage Determination

```
Analysis
                                              Grid type: Global
                                              Cell size: 10 km
                                   Study point location: Cell center
                Move study point to nearest Census point: No
                     Default service area method:   U.S.: Constant distance
          Distance or percent for default method:   U.S.: 300 km or %
                        Maximum desired signal distance: 300 km
                               Cap TV D/U ramp function: No
                               TV D/U ramp function cap: 8 dB
                          Include DTS self-interference: No

CDBS/LMS
                                         Respect DA flag: No
                            HAAT radial count:   U.S.: 8

Search
                  Check individual DTS transmitter distances: No
                                      Co-channel MX distance: 5 km
                  Rule limit extra distance less than low ERP: 80 km
                                          Rule limit low ERP: 0.2 kW
                  Rule limit extra distance low to medium ERP: 100 km
                                       Rule limit medium ERP: 1.5 kW
                 Rule limit extra distance medium to high ERP: 130 km
                                         Rule limit high ERP: 15 kW
              Rule limit extra distance greater than high ERP: 178 km
                    Use maximum signal distance as rule extra: No
                                   Spherical earth distance: 111.15 km/deg

Contours
                          Contour radial count:   U.S.: 360
          Digital TV full-service contour, UHF:   U.S.: 10 dBu

                     Use UHF dipole adjustment:   U.S.: No
                       Dipole center frequency:   U.S.: 539 MHz

FCC Contours
                                Average terrain database: 1-second
             Average terrain profile resolution:   U.S.: 10 pts/km
                        Use elevation patterns:   U.S.: Full-service TV only
                   Use real elevation patterns:   U.S.: No
                        Derive azimuth pattern:   U.S.: No
                      FCC curve set, TV digital:   U.S.: F(50,90)
             Lookup method below curve minimum distance: Free-space
                      Contour HAAT radial count:   U.S.: 8
                                  Minimum HAAT:   U.S.: 30.5 m
                 Average terrain start distance:   U.S.: 3.2 km
                   Average terrain end distance:   U.S.: 16.1 km
                             Truncate DTS service area: No
                              DTS distance limit, UHF: 103 km

L-R Contours
                                       Terrain database: 1-second
                                     Profile resolution: 10 pts/km
                         Calculation distance increment: 0.1 km
                                     Digital % location: 50 %
                                         Digital % time: 90 %
                                   Digital % confidence: 50 %
                                    Receiver height AGL: 1.5 m
                                    Signal polarization: Horizontal
                              Atmospheric refractivity: 301 N
                                    Ground permittivity: 15
                                   Ground conductivity: 0.005 S/m
                                           Service mode: Broadcast
                                           Climate type: Continental temperate

Patterns
```

```
             Depression angle method:   U.S.: True geometry
            Use mechanical beam tilt:   U.S.: Always
     Use generic patterns by default:   U.S.: Yes
             Mirror generic patterns:   U.S.: Never
       Beam tilt on generic patterns:   U.S.: Offset
               Invert negative tilts:   U.S.: Yes
            Digital receive antenna f/b, UHF: 0 dB
```

```
Propagation
                          Terrain database: 1-second
                Profile resolution:   U.S.: 10 pts/km
                                    Canada: 1 pts/km
                                    Mexico: 1 pts/km
              Model error handling:   U.S.: Disregard
                       Receiver height AGL: 1.5 m
            Minimum transmitter height AGL: 1.5 m
                Digital desired % location: 50 %
                    Digital desired % time: 90 %
              Digital desired % confidence: 50 %
                       Signal polarization: Horizontal
                  Atmospheric refractivity: 301 N
                       Ground permittivity: 15
                       Ground conductivity: 0.005 S/m
                              Service mode: Broadcast
                              Climate type: Continental temperate
```

```
Service
                    Set service thresholds: Yes

 Digital TV full-service threshold, UHF:   U.S.: 24.4 dBu
              Use UHF dipole adjustment:   U.S.: No
                Dipole center frequency:   U.S.: 539 MHz
```

```
Clutter
                 Apply clutter adjustments: No
```