ATIS-0500030

Guidelines for Testing Barometric Pressure-Based Z-Axis Solutions

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ATIS-0500030, *Guidelines for Testing Barometric Pressure-Based Z-Axis Solutions*

Is an ATIS Standard developed by the **Emergency Services & Methodologies (ESM)** Subcommittee under the **ATIS Emergency Services Interconnection Forum (ESIF)**.

Guidelines for Testing Barometric Pressure-Based Z-Axis Solutions

Alliance for Telecommunications Industry Solutions

Approved May 25, 2016

Abstract

This document provides broad guidelines for testing barometric pressure-based altitude (z-axis) measurement systems, which are being proposed to enable more accurate and more actionable indoor wireless 911 location.

Foreword

The Alliance for Telecommunications Industry Solutions (ATIS) serves the public through improved understanding between carriers, customers, and manufacturers. The Emergency Services Interconnection Forum (ESIF) provides a forum to facilitate the identification and resolution of technical and/or operational issues related to the interconnection of wireline, wireless, cable, satellites, Internet and emergency services networks.

The mandatory requirements are designated by the word *shall* and recommendations by the word *should*. Where both a mandatory requirement and a recommendation are specified for the same criterion, the recommendation represents a goal currently identifiable as having distinct compatibility or performance advantages. The word *may* denote an optional capability that could augment the standard. The standard is fully functional without the incorporation of this optional capability.

Suggestions for improvement of this document are welcome. They should be sent to the Alliance for Telecommunications Industry Solutions, ESIF, 1200 G Street NW, Suite 500, Washington, DC 20005.

At the time of consensus on this document, ESIF, which was responsible for its development, had the following leadership:

T. Reese, ESIF Chair (Ericsson)

J. English, ESIF 1st Vice-Chair (APCO International)

S. Sherwood, ESIF 2nd Vice-Chair (Verizon Wireless)

J. Green, ESIF ESM Co-Chair (Sprint)

K. Springer, ESIF ESM Co-Chair (AT&T)

The **Emergency Services & Methodologies [ESM]** Subcommittee was responsible for the development of this document.

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1   Introduction

With the increased prevalence of using wireless handsets to call 911 from indoor locations and the increased proportion of callers who rely exclusively on wireless in their homes, the criticality of obtaining reliable caller height information and relaying it to emergency dispatchers has taken heightened importance. New technologies have emerged to tackle the challenges of providing accurate z-axis information and are vying to be included in wireless networks to meet this need.

This heightened importance of accurately measuring and relaying altitude information to public safety emergency responders is reflected in the FCC's 4th Report and Order, which established timelines for the wireless industry to define metrics for achievable z-axis (altitude) accuracy, and must be derived from "an independently administered and transparent test bed process" to be implemented in the test bed being established to characterize indoor wireless location.

ATIS in its traditional role of creating timely consensus solutions to challenging requirements has tackled this topic of creating a standard set of methodology guidelines for testing z-axis solutions, particularly those that are currently the most likely to be deployed, which are based on barometric pressure measurements. This document presents these consensus test guidelines.   It builds on the various existing ATIS documents tackling indoor wireless location testing and articulates guidelines specifically targeted to testing the altitude component in the wireless E911 context.

2   Scope, Purpose, & Application

2.1   Scope

This document presents guidelines for testing z-axis (i.e., altitude) accuracy for systems that use barometric pressure-based sensors in the handset. Focus is placed on systems where the measured altitude is derived from compensated barometric pressure measurements, i.e., where the error sources in the pressure measurement are compensated for by the location system under test and where the altitude result is expressed in units of distance, i.e., in meters, rather than a raw measurement in units of atmospheric pressure, e.g., hectopascal or millibar.

This document clearly identifies the various salient sources of barometric pressure measurement errors and proposes test methods that ensure that those effects are accounted for in the design of the tests and that their effects are manifested in statistically representative test samples.

Non-barometric pressure z-axis or altitude measurement systems, which are currently less likely to be relied upon in the near to intermediate term, or are less mature than barometric pressure systems are not addressed in this document, and they may be addressed in future ATIS test methodology standardization efforts as the need arises.

2.2   Purpose

The purpose of this document is to provide broad guidelines for testing barometric pressure-based altitude (z-axis) measurement systems, which are being proposed to enable more accurate and more actionable indoor wireless 911 location.   This document is not intended to provide detailed test procedures but rather creates the framework upon which such detailed, technology specific z-axis test procedures can be readily developed. A primary purpose for this document is to enable technologist, wireless carriers and test organizations to create consistent, representative test procedures that appropriately capture the key environmental and operational effects impacting the accuracy of altitude (z-axis), barometric pressure-based solutions in the context of indoor wireless E911.

2.3 Application

The guidelines presented in this document testing should be followed by those intending to test barometric pressure-based solutions for wireless E911. In particular, these guidelines should be followed in defining the detailed test procedure for z-axis testing to take place as part of the indoor test bed created to meet the requirements in the FCC's 4th Report and Order. It is also recommended that z-axis technologists and system solution providers that would like to be considered for providing barometric pressure-based z-axis capabilities for wireless E911, subject their systems to testing that follows these guidelines.

3 Normative References

The following standards contain provisions that, through reference in this text, constitute provisions of this Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below.

FCC 15-9, PS Docket No. 07-114, 4th Report and Order, *Fourth Report and Order In the Matter of Wireless E911 Location Accuracy Requirements*[1]

ATIS-0500011, *Location Technology Performance Data – Define Topologies & Data Collection.*[2]

ATIS-0500013, *Approaches to Wireless E9-1-1 Indoor Location Performance Testing*[3]

ATIS-0500022, *Test Plan Input for a Location Technology Test Bed*[4]

4 Definitions, Acronyms, & Abbreviations

For a list of common communications terms and definitions, please visit the *ATIS Telecom Glossary*, which is located at < http://www.atis.org/glossary >.

4.1 Definitions

Pascal: Metric (SI) unit for pressure equal to one newton per square meter (N / m2). In metrology scaled by 100s and expressed in units of hectopascals which is equivalent to the older unit of pressure one millibar (mbar).

Stack Effect: Movement of air into and out of buildings that results from air buoyancy caused by pressure differential which is caused by temperature and humidity differences between inside and outside of a building.

Standard atmosphere (atm): The value of atmospheric pressure at earth mean sea level and is defined as 101,325 Pa or 1,013.25 hPa.

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[1] This document is available from the Federal Communications Commission, 445 12th Street, SW, Washington, DC 20554: < http://www.fcc.gov >.

[2] This document is available from the Alliance for Telecommunications Industry Solutions, 1200 G Street, NW Suite 500 | Washington, DC, 20005: < https://www.atis.org/docstore/product.aspx?id=22697 >.

[3] This document is available from the Alliance for Telecommunications Industry Solutions, 1200 G Street, NW Suite 500 | Washington, DC, 20005: < https://www.atis.org/docstore/product.aspx?id=25009 >.

[4] This document is available from the Alliance for Telecommunications Industry Solutions, 1200 G Street, NW Suite 500 | Washington, DC, 20005: < https://www.atis.org/docstore/product.aspx?id=27856 >.

4.2 Acronyms & Abbreviations

ATIS	Alliance for Telecommunications Industry Solutions
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAE	Height Above Ellipsoid
HVAC	Heating, Ventilation, & Air Conditioning
hPa	hectopascal – hecto (100s) of pascals
MSL	Mean Sea Level
PSAP	Public Safety Answering Point
UBP	Uncompensated Barometric Pressure

5 Testing Vertical Height Best Practices

In outdoor emergency situations, vertical height reporting has not been widely used since most emergencies were at ground level and the x-y or latitude, longitude position guided the emergency responder. Indoor emergencies have the added complexity of potentially many floors of a building that need to be searched to find a non-responsive victim.

Today, two primary sources of vertical or height (Z) information are envisioned, one provisioned and one measured. A provisioned entry is a manually entered height value, corresponding to some external value. An example would be the floor information attached to the civic address in a provisioned Wi-Fi MAC address lookup database. Provisioned entries do not change between fixes, even if the user changes floors, but still reports the same MAC address. A measured source of vertical height example is altitude in meters based on the barometric pressure sensor in the handset or other sources. The measured value could differ from call to call as the environment changes or the user moves vertically.

Other technologies that have been mentioned as possible sources of z-axis information are dead reckoning sensor based systems and hybrid combination of GPS vertical measurement with another technology. Those solutions are not yet understood well enough to permit the development of detailed test bed best practices. However, those and other technologies can be explored in future testing programs as their maturity allows.

This document uses the baseline of the horizontal x-y (latitude/longitude) testing regime and suggests the minimum amount of additional effort to be expended or data to be collected to adequately characterize z-axis performance. These recommendations are based on the unique error sources for the specific z-axis technology to be focused on in this document, which is barometric pressure-based height measurements. Note that the scope of the recommendation here will cover only reporting the height in meters above sea level, not the errors that could be encountered in converting a local terrain height to a building floor level.

5.1 Measured Barometric Pressure-Based Considerations

Several sources of information have been used to generate the list of considerations below. The CTIA Z-Axis Working Group submitted a document that captured industry experience and literature research summaries. Qualcomm submitted a contribution as well which provided the detailed test methodology used to collect sample results in San Francisco with ranges of numerical values for various error sources. These results are not included in this report since they were not third party supervised by ATIS, but have been useful to rank probable error sources as listed in Annex B.

Two variants of barometric pressure height are referenced in the FCC's 4th Report and Order. The first is uncompensated barometric pressure (UBP) in pressure units such as hectopascals or millibars, measured by the handset and reported to the PSAP with no compensation or correction in the core network. This is to enable a first responder to go into the same building and go up or down until their pressure reading matches and they should be close to the incident. There is no testing specifically described in this document for UBP. The second variant is measured height derived from compensated barometric pressure measurements, which provides altitude in meters and is the subject of these test guidelines.

Based on public safety needs, the preferred approach to testing the vertical position is in the height domain (meters) rather than the pressure domain (hectopascal or millibars). Having a professionally surveyed altitude, e.g., accurate to 10 cm, will be the ground truth reference. The systems under test will produce height estimates and will be compared to this ground truth value.

Black box testing (testing the output of the box, not the internals) of the system is desired; i.e., no need to evaluate how the intricacies of the compensation scheme elements perform. Thus, no separate measurement of intermediate results from various error sources is required. Use of the testing guidelines, outlined in this document will reflect the combined effect of the top three error sources, which are weather, device bias, and indoor building effects, such that results can be extrapolated to areas outside of the testbed, provided a comparable deployment of the compensation system is present in those areas.

Specific attributes of these top three error sources are described below and should be taken into account in test bed planning.

5.1.1 Weather Effects

The specific test parameters for randomization during testing are:

- Full range of barometric pressure experienced during a year.
    - Nominal value is 1013.25 hPa, with values greater than 1020 being *high*, and values below 1010 considered *low*.
    - However, *low* versus *high* depends on relative geographical distribution of levels (e.g., a value of 1020 can be *low*, because it is surrounded by a ring of 1025 values).
- Full range of wind conditions as a measure of stable or unstable conditions.
    - Stable conditions with no wind are usually associated with high pressure. Unstable conditions with varying wind speeds are more associated with low pressure.
    - Strong winds can cause pressure variations inside of buildings.
- Full range of temperature conditions experienced during a year.
    - San Francisco can be tested year-round due to its limited temperature variation and large wind fluctuations.
    - Atlanta should be tested in the winter and, if practical, in the summer months as well to assess larger indoor/outdoor temperature differential.
    - A few test sites in a northern city, such as Chicago during extremely cold weather, may be necessary to supplement the testing in Atlanta and San Francisco.

Test schedule planning is required for the general season (winter versus summer), but weather changes over a multi-week collection cycle are expected to vary enough to provide sufficient randomization. The recommended approach is to observe and record the general weather conditions as either stable or unstable, and confirm that there has indeed been sufficient representation of both conditions during testing. Particular attention to results from tall (over 10 story) sealed buildings in both calm and high wind conditions should be tested. Upon completing the test program, if assessing the contemporaneous record reveals a particularly benign weather period, then consideration should be given to repeat testing scheduled to coincide with expected unstable conditions.

Reference data collection from weather stations in the test area should include:

- Barometric pressure level and pressure tendency (stable, rising, falling),

- Wind speed (average, min, max), and

- Temperature (min, max, average).

Weather reference network density, frequency of update, and accuracy of surveyed reference altitude all impact correction accuracy in a compensated barometric z-axis system. For test results from the test bed to be extrapolated to areas outside of the test bed, at a minimum the compensation network vendor or wireless carrier must be able to certify that these three compensation factors are consistent with those present in the test bed locations. On a more general point, other compensation complexities, including temperature, humidity, wind, building databases, etc. may also impact the accuracy of compensation, and no test bed results can be extrapolated unless the vendor or carrier provides assurances that comparable compensation techniques and network capabilities are present in the non-testbed areas.

5.1.2 Handset barometric pressure device bias and drift attributes

Bias in the pressure sensor device contained in the handset will show up as a consistent error in height (high or low) compared to the surveyed truth. Randomization across the following parameters will aid characterization of this effect:

- Use multiple handsets during a single test, and compare the results from different models.

- Use handsets with pressure sensors from at least the dominant sensor vendors (Bosch and STMicro) which account for the majority of market share in the US.   Other sensor manufacturers should be included if available.

- Use handsets across price tier (high and low) as a proxy for the sensors being calibrated at the factory or not.

- Use handsets available today in volume.

- Test multiple handsets at the same time, so phone bias in each case can be separated from other error sources.

- Some proportion of test handsets should include phones manufactured at least one year prior to the test in order to identify whether aging or drift significantly impact bias and produce outlier results.

Phone operating mode may affect barometric pressure values. Some indications in the literature and various experiments show interactions between the barometric pressure measurement and other phone sub-systems. It is suggested that the handsets be operated simulating an emergency 911 call. Specifically:

- Dialing a 911 call simulator to activate GPS and any other location technology systems or heat generating components resident on the handsets should appropriately account for these effects during testing. This testing approach is consistent with current x-y testing approaches which simulate a 911 call when taking x-y location fixes.

5.1.3 In-Building Effects

Pressure inside of a building can be different than pressure outside it due to HVAC (Heating Ventilation & Air Conditioning) from fans forcing air into or out of the building. Additional pressure differential due to temperature and moisture differences between inside and outside of a building is known as the stack or chimney effect. The stack effect is most pronounced when the outside air is cold and very dense, while the air inside of the building is heated and less dense. Cold air flows into the building and the warm air rises within the building. This can cause pressure differences between inside and outside of the building as a function of building height, architectural ventilation zones, and how well sealed the building is.

ATIS-0500011, ATIS-0500013, and ATIS-0500022 address building variability from an RF penetration perspective, but not a barometric pressure perspective. In addition to the building variability selection criteria specified for horizontal location testing, acceptable vertical location testing requires that test bed building selection include an appropriate representation of HVAC managed (sealed) versus un-managed buildings, particularly for taller test buildings 10 stories or greater. This can largely be accomplished by including both newer construction and older construction in the test buildings selected.

5.1.4 Test Point Selection, Sample Size, Test Duration, and Instrumentation

The generalized instructions for site selection in ATIS-0500011 and ATIS-0500013 should provide the following randomization already:

- Rural, Suburban, Urban, Dense Urban.

- Building Height.
    - Low RF penetration Loss – 1 to 2 story.
    - Moderate RF penetration loss – first or second floor of a 4 to 8 story building.
    - High RF penetration loss – underground parking lots, inner offices of high rise buildings.

ATIS-0500013, clause 5 defines:

- Residential (single family, multi-family 2-4 story, and multi-family multi-story).

- Commercial (1-2 story, multi-story).

- Number of test points range from 1 to 6 depending on building complexity.

ATIS-05000013, clause 6 describes the planning process for Number of Test Points and Time interval between Test Calls:

- 2 test points for a single family residence, to 6 test points (low/medium/high x periphery/core) for a tall building.

- 30 to 100 test calls.

- Call duration 30 seconds or until complete – with a typical test site taking approximately an hour, although due to pauses required between test calls this duration could be two hours.

This number of test points and calls per test point are expected to sufficiently capture both the errors due to weather compensation and handset device bias effects. The sample size of 30 to 100 independent samples (test calls) recommended for x-y technologies is large enough to describe both the mean and standard deviation of the sensor over the observation period. In contrast to x-y location technologies that operate indoors with outdoor emitters and suffer corrupted signals due to absorption, reflection, and diffraction and often have high positioning error variance, the variance in height measurement of a barometric-based device per call at any given point is expected to be quite small relative to the height of a single floor.

Each individual barometric pressure report appears to be independent at the handset. There is some low pass filtering in the sensor that removes high frequency noise, but the time duration of the filter is short compared to the typical call duration of 10 to 30 seconds. This means that there is no sharing of information between each barometric pressure report across multiple calls, rendering the samples independent.

The duration over which the 30 to 100 samples are collected ideally should capture the device behavior and the changes within a building, as well as weather dynamics. These longer duration effects can effectively be captured by using the whole body of collected data amongst various buildings and floors, in a variety of quiet and unsettled conditions. To confirm this basic test plan tenet, one or two test sites may be run for 12 to 24 hours, with all test handsets running simultaneously, to confirm there is no phone-specific variances or combinations of weather or indoor conditions that would only be seen in a long duration data collection. Data results from a 16-hour overnight collection in unsettled weather conditions supports the idea that all the handsets show consistent behavior over long periods with no change in mean or standard deviation of z-axis error as a function of observation interval.

In-building HVAC and stack effects, however, may cause pressure differences that vary up the vertical building profile in an unpredictable manner. Thus, some additional test points should be used to assess whether this variation is sufficiently captured by the "low/middle/high" floor test points, or if larger variation is present and additional testing is required in certain building types (primarily tall sealed buildings). This additional testing can be fewer (e.g., 20) fixes, every couple of floors (every other floor or every 3rd floor), possibly using interpolated

vertical ground truth to minimize professional survey costs. The average phone height error plotted against floor number should reveal any floor level correlated HVAC or stack effects that would not be revealed by just the (low/medium/high) test points. If the low/middle/high variations reasonably capture the variations revealed in the more granular test samples, then ongoing vertical testing may rely solely upon the low/medium/high test points utilized for horizontal testing.

It is advantageous for subsequent data analysis to have an accurate measurement of the ambient barometric pressure at the test point. It is therefore recommended that the test setup (the test handset tray or cart) be equipped with a lab quality calibrated barometer. One example that was used effectively in recent Qualcomm tests is Model 745 from Paroscientific Inc. The readings from this reference barometer should be recorded at each test point during the testing.

5.1.5 Rural Testing Consideration and 80% of population across top 50 CMAs

Carriers will need to determine if vertical height reporting is required in rural areas of the top 50 CMAs to meet the 80% population coverage requirement.

To support this determination, the vertical yield of all systems under test should be collected for all morphologies and all test points.

Rural environments are expected to have only 1 to 2 story buildings, and thus height reporting is less important in emergency situations. There are some unusual outdoor search and rescue scenarios where altitude reporting would aid in a GPS/RF shadowed valley, however those fall outside of the FCC's 4th Report and Order mandate and are not addressed here.

6   Annex A – Background Material on Various Error Sources

The following clause provides background material on weather and various barometric pressure error sources. The discussion is meant to be informative rather than prescriptive.

Temperature differences cause regions of low and high pressure

A primary weather effect is caused by high versus low atmospheric pressure. As air warms, it rises, causing a low pressure region at the surface. When air cools, it descends causing a high pressure region on the surface.
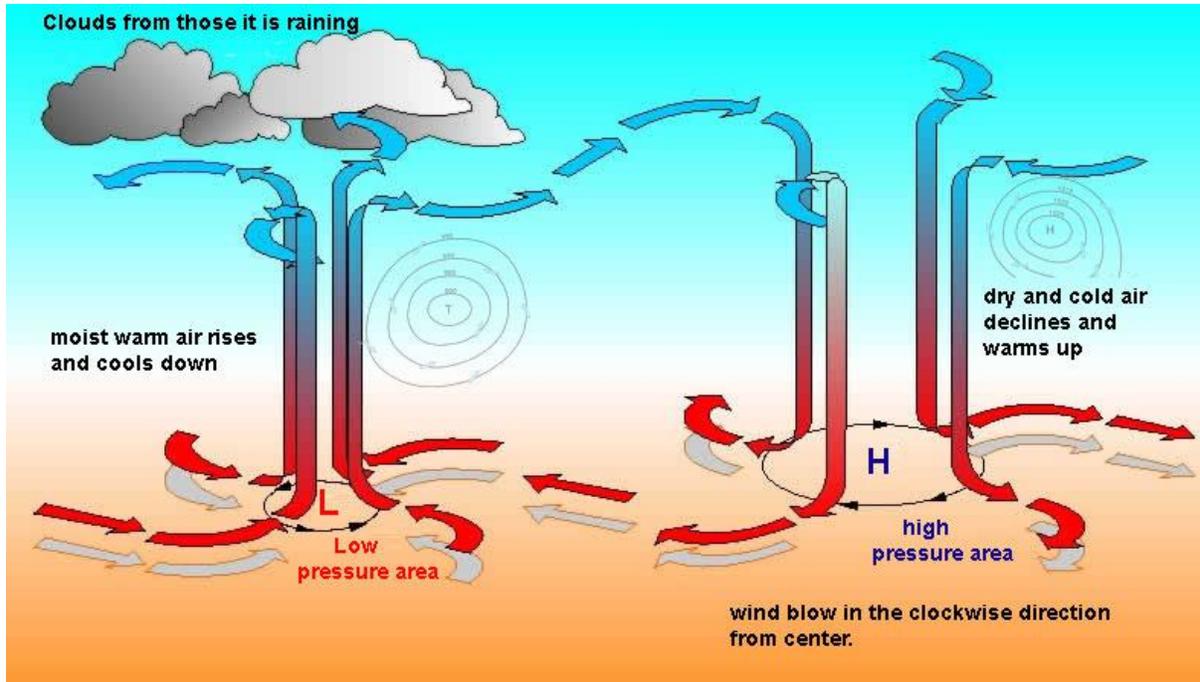

Figure 1 – High Low Pressure Areas[5]

Wind[6] flows from areas of high pressure to areas of low pressure[7]. This is due to density[8] differences between the two air masses[9]. Since stronger high-pressure systems contain cooler or drier air, the air mass is denser and flows towards areas that are warm or moist, which are in the vicinity of low pressure areas in advance of their associated cold fronts[10]. The stronger the pressure difference or pressure gradient, between a high-pressure system and a low-pressure system, the stronger the wind.[11]

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[5] This image is available from meteoblue, Basel, Switzerland at: < https://content.meteoblue.com/en/meteoscool/large-scale-weather/high-low-pressure >

[6] Available at: < https://en.wikipedia.org/wiki/Wind >.

[7] Available at: < https://en.wikipedia.org/wiki/Low-pressure_area >.

[8] Available at: < https://en.wikipedia.org/wiki/Density >.

[9] Available at: < https://en.wikipedia.org/wiki/Air_mass >.

[10] Available at: < https://en.wikipedia.org/wiki/Cold_front >.

[11] Available at: < https://en.wikipedia.org/wiki/High-pressure_area#Connection_to_wind >.

7 Annex B: Tabulation of Error Sources

The following table summarizes various error sources that were considered during the data review process. The 3 main error sources described above (weather, device bias, and indoor building stack effects) were considered as having the largest effect in vertical height accuracy and thus needed to be measured during the testing effort.

Mobile Barometric Pressure Sensor Accuracy

- Measurement biases

- Measurement noise

- Measurement drift over time

- Measurement error as a function of sensor device temperature (i.e., the mobile is hot because it has been in a call)

Building Effects

- Pressure discontinuities caused by uneven HVAC effects and other factors

Reference Barometer Quality

Mobile to Reference Station Distance

Reference Measurement Time Delays

Quality and resolution of the terrain altitude database

Impact of mobile position inaccuracies on terrain database lookup

Completeness of building-related databases

Floor level (height) non-linearities

Errors caused when moving between different forms of representing altitude

8 Annex C: Weather Differences Between San Francisco, Atlanta, & Chicago

Atlanta has 20% of time in summer months with temperatures above 85 degrees and 20% of time in winter months with temperatures below freezing. Atlanta has daily median/max wind speeds of 10/17 mph in the winter and 7/12 in the summer.[12]   San Francisco, by comparison, has only minimal periods with temperatures either below freezing or above 85 degrees, although it has strong winds with daily median/max speeds of 14/24 mph in the summer and 7/13 in the winter.[13]   The San Jose and Silicon Valley portions of the San Francisco Bay Area test bed region provide somewhat warmer and colder temperatures than San Francisco proper, but would generally still be considered mild.[14]   Although some other markets, such as Chicago, have been discussed, Chicago's wind speeds are similar to San Francisco's and its high temperature points in summer are significantly less than Atlanta. Chicago does, however, provide some periods of winter temperatures below 15 degrees (frigid) which Atlanta reaches significantly less frequently.[15]

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[12] This data is available from Cedar Lake Ventures, Inc., 4 Embarcadero Center, Suite 1400, San Francisco, CA 94111 at: < https://weatherspark.com/averages/29669/Atlanta-Georgia-United-States > .

[13] This data is available from Cedar Lake Ventures, Inc., 4 Embarcadero Center, Suite 1400, San Francisco, CA 94111 at: < https://weatherspark.com/averages/31587/San-Francisco-California-United-States >.

[14] This data is available from Cedar Lake Ventures, Inc., 4 Embarcadero Center, Suite 1400, San Francisco, CA 94111 at: < https://weatherspark.com/averages/31616/San-Jose-California-United-States >.

[15] This data is available from Cedar Lake Ventures, Inc., 4 Embarcadero Center, Suite 1400, San Francisco, CA 94111 at: < https://weatherspark.com/averages/30851/Chicago-Illinois-United-States >.

9 Annex D: Differences Between Ellipsoidal & Orthometric Height Systems

There is no single way of representing altitude, complicating matters, and sometimes causing confusion that turns into error.

- The GNSS industry uses Height Above Ellipsoid (HAE) to represent altitude.
- PSAPs, the weather industry, surveyors, and many terrain and building databases currently use orthometric height (known as above Mean Sea Level (MSL)) to represent altitude.

PSAPs will prefer orthometric height for floor determination, but the GPS based standards typically deliver it in HAE. Conversion from HAE to orthometric height (MSL) requires accurate knowledge of position, which is used to look up a correction factor known as Geoid Height (N) in a Geoid grid database. Two such databases in common use today are:

- EGM96 – 15 min spacing – 16 squares per degree – coarser, less precise, thus up to 3 meters of error.
- GEOID12 – 1 min spacing – 3600 squares per degree – can achieve 1 cm accuracy with cubic spline interpolation. (Note that GEOID12 is a more recent, more accurate source than GEOID03 used in Figure 2 for illustration.)

Orthometric Height

The orthometric height (H) of a point is the distance H along a plumb line from the point to the geoid. The geoid is the equipotential surface that would coincide with the mean ocean surface of the Earth if the oceans and atmosphere were in equilibrium, and thus is influenced by variable crust density and gravity.
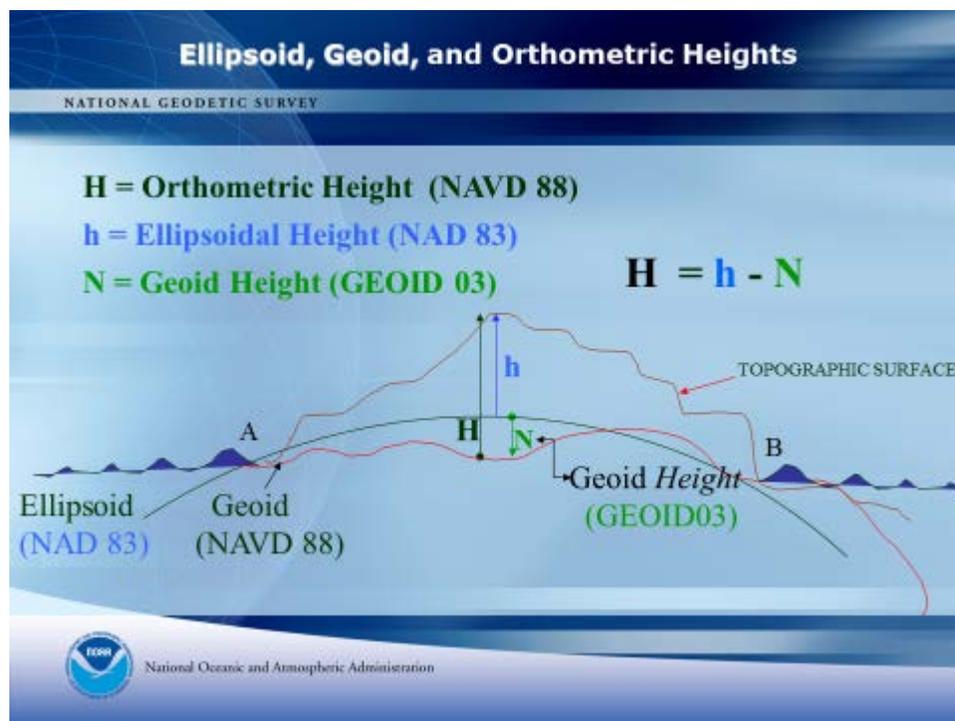

Figure 2 – Orthometric Height[16]

Height Above Ellipsoid

Height Above Ellipsoid as used in GNSS systems is the distance above a globally defined reference ellipsoid. It does not take into account crust density or gravity, thus it does not necessarily align with the geoid.
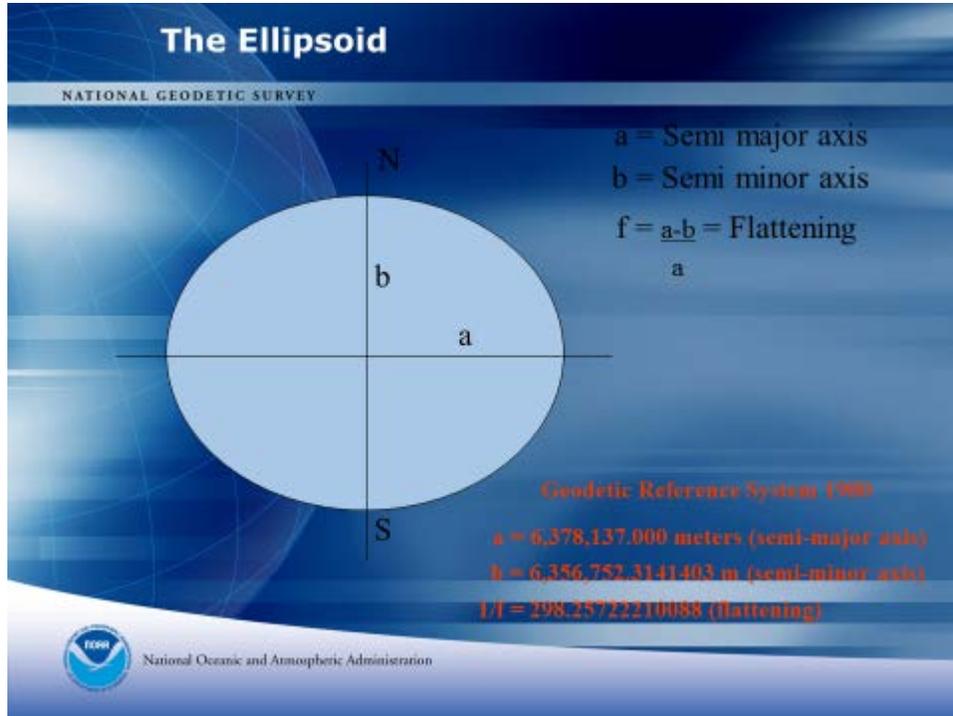

Figure 3 – Height Above Ellipsoid[17]

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[17]   This   image   is   available   from   the   National   Geodetic   Survey,   Silver   Spring,   MD   at: <http://www.ngs.noaa.gov/GEOID/PRESENTATIONS/2007_02_24_CCPS/Roman_A_PLSC2007notes.pdf >