Ground Architecture and Airport Installation

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Abstract

This document gives the ground equipment installation requirements as identified in the SESAR 15.3.6 project. It is intended to be a high level description and architecture document, independent of any particular airport or ground subsystem manufacturer. The purpose of the document is to provide ANSPs with an analysis of the ground architecture and airport installation issues for a GAST D ground station. The scope is, based on the present status of standards and development, to describe the challenges related to a GAST D airport installation, and to identify the main differences with a GAST C installation. The contributions to this document is based on studies, general experience and participation in international discussion and standardisation bodies, but as none of the participants have any experience with GAST D installations in practice, it is expected that further development and testing will provide more details on siting requirements.

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Executive summary

This document provides ground equipment installation requirements as identified in the SESAR 15.3.6 project. It is intended to be a high-level description and architecture document, independent of any particular airport or ground subsystem manufacturer.

A general description of airport architecture will be presented, with usual facilities and infrastructure. A further classification of types of airports has been performed.

As the long-term operational system in view is GBAS CAT II/III, special requirements will be linked to receiving conditions for GNSS signals as well as VDB transmitter and receiver conditions. The main challenges and differences in comparison to GBAS CAT I are highlighted. This is closely linked to environmental conditions influencing the signals, like natural or manmade obstacles, different weather conditions etc.

Control and monitoring units are other key points in an airport installation, originating from operational needs. Air traffic control may be performed locally or remotely, and it is necessary to sort out which status messages, which operational actions, which configuration parameters, which maintenance actions, may be accessed where and by whom.

The siting process will also be treated. The siting process requires concrete requirements for site selection and survey. The site acceptance will depend on fulfilment of requirements for the ground subsystem and GNSS antenna installations and validation of specific coordinates. These requirements will be sought qualified in this document, and if possible, also quantified.

Finally, the requirements for a GAST D installation, where they differ from a GAST C installation, have been collected and are summarised in the last section. It should be noted that they are not yet part of any standard, they have not been tested and qualified, as they are the result of this study where none of the participants have any experience with GAST D installations in practice. The document is complete with respect to the current knowledge, but it is expected that achievement within the final stage of 15.3.6, i.e. the validation phase, will provide some more details regarding siting requirement. It is especially the validation of monitor design and the aspects related to VDB ground coverage which are expected to impact on the requirements.

1 Introduction

1.1 Purpose of the document

In general, a GBAS ground station is very flexible when it comes to siting, for instance compared to an ILS which must be sited at specific locations, and occupies significant areas on those locations for each and every runway end. A GBAS ground station has some restrictions with respect to distance between its elements (GNSS reference antennas/receivers, VDB antenna/transmitter, etc.), maximum distances to decision points or thresholds and minimum distances to operational areas: But other than that it can be located quite independently from the runway ends it serves. Although this siting flexibility is beneficial with respect to complex airport layouts and pressure on airport real estate, it backfires in the sense that no area is being specifically allocated to GBAS when new airports are being planned, and no specific area is normally being reserved for a GBAS ground station when making changes to airport layout. This, along with the requirement that line-of-sight from a VDB transmitter antenna to operational areas is generally required, can make it challenging to site a GBAS ground station.

GBAS ground stations from different manufacturers are based on different architectures, and the siting requirements will depend on the architecture of the ground station in question.

This deliverable is aimed at identifying the high level, general ground architecture of a GBAS CAT II/III airport installation, and the main differences with a GBAS CAT I installation. The study and the development performed within this project are based on GBAS GAST C, and further aimed at identifying in which aspects modifications are necessary in order to obtain GAST D performance. The document is complete with respect to the current knowledge, but it is expected that achievement within the final stage of 15.3.6, i.e. the validation phase, will provide some more details regarding siting requirement. It is especially the validation of monitor design and the aspects related to VDB ground coverage which are expected to impact on the requirements.

The focus will be on the installation of such a ground station related to airport infrastructure. A general airport infrastructure is presented, before the general GBAS ground station is presented. Based on the GBAS ground station system requirements derived in D03 [6] of this project, this deliverable will present the requirements one level above, i.e. it mainly focuses on the GBAS ground facility, the siting and installation issues, and well as the implementation of control and status functions.

One chapter is entirely dedicated to the special challenges presented by the errors that are uncorrelated between the aircraft and the ground station, such as multipath, radio frequency interference, atmospheric disturbances etc. Proper siting may mitigate some of these, but not all. Those that cannot be met by proper siting will require monitoring.

A siting process for the airport installation of a GBAS GAST D ground station is proposed, before we finally summarise the candidate requirements for GAST D, where they differ from GAST C.

As already mentioned, the D03 document, “High Level Performance Allocation and Split of Responsibilities between Air and Ground,” is an important input to this task, and was concluded in a very early phase of this task. D16, “System validation plan”, is another source document. T16 early made an effort to provide some preliminary input by drafting the document [3]; Siting Discussion Paper, as an input to T04, as T16 mostly run in parallel to this task. Finally, 15.3.6 D20, [27], has been a reference on equipment control and status interfaces.

1.2 Intended readership

This document is mainly intended for internal use in WP15.3.6, in particular ANSPs and manufacturers will be directly concerned by the implications of airport installation and siting.

1.3 Inputs from other projects

The 15.3.6 deliverables D03 and D16 [65] have given a valuable basis for the work performed on this deliverable, D04, in addition to documents provided by the SESAR project WP9.12.

1.4 Glossary of terms

NA

1.5 Acronyms and Terminology

Term	Definition
AC	Alternating Current
ADB	Additional Data Block
ACSF	ATC Control and Status Function
ACSU	ATC Control and Status Unit
AENA	Aeropuertos Españoles y Navegación Aérea
AFIS	Aerodrome Flight Information Service
ANSP	Air Navigation Service Provider
APME	A-Posteriori Multipath Estimation
ARNS	Aeronautical Radio Navigation Services
ASCII	American Standard Code for Information Interchange
ATC	Air Traffic Control
ATCO	Air Traffic COntroller
ATCU	ATC Unit (identical to ACSU)
ATM	Air Traffic Management
BRA	Building Restricted Area
C/A	Coarse/Acquisition (code)
CAT	Category
CCD	Code Carrier Divergence
COCR	Common Outage Capacity Region
CONOPS	Concept of Operations
CONUS	Conterminous United States ionospheric threat model
CP	Code-Phase
CMC	Code Minus Carrier
C/N_0	Signal Carrier to Noise spectral density ratio

Term	Definition
CRC	Cyclic Redundancy Check
CW	Continuous Wave
DC	Direct Current
DD	Double Differences
DME	Distance Measuring Equipment
DFS	Deutsche Flugsicherung GmbH
DSNA	Direction des Services de la Navigation Aérienne
EANPG-FMG	European Air Navigation Planning Group- Frequency Management Group
E-ATMS	European Air Traffic Management System
EIRP	Equivalent Isotropic Radiated Power
EL	Elevation
E-L	Early - Late
EMC	Electromagnetic Compatibility
ESD	ElectroStatic Discharge
EUROCAE	European Organisation for Civil Aviation Equipment
FAA	Federal Aviation Administration
FAA AC	FAA Aircraft Certification
FAS	Final Approach Segment
FAST	Facility Approach Service Type
FASLAL	FAS Lateral Alert Limit
FIR	Finite Impulse Response (filtering)
FFM	Far Field Monitor
FM	Frequency Modulation
FTP	Fictitious Threshold Point
GAD	Ground Accuracy Designator (curves)
GAST	GBAS Approach Service Type
GBAS	Ground Based Augmentation System

Term	Definition
GBAS GS	GBAS Ground Subsystem
GNSS	Global Navigation Satellite System
GPA	Glide Path Angle
GPIP	Glide Path Interaction Point
GPS	Global Positioning System
GPS-INS	GPS Inertial Navigation Systems
GRP	GBAS Reference Point
GS	Ground Subsystem
HAT	Height Above Threshold
IAP	Instrument Approach Procedures
ICAO	International Civil Aviation Organization
ICAO NSP	ICAO Navigation System Panel
IEA	Ionospheric Equatorial Anomaly
IEEE	Institute of Electrical and Electronics Engineers
IFM	Ionospheric Field Monitor
IFR	Instrument Flight Rules
ILS	Instrument Landing System
ION	Institute Of Navigation
LCSF	Local Control and Status Function
LCSU	Local Control and Status Unit
LMDT	Local Maintenance and Data Terminal
LNA	Low Noise Amplifier
LOCA	Local Object Consideration Area
LOS	Line Of Sight
LTP	Landing Threshold Point
MDT	Maintenance Data Terminal
MEDLL	Multipath Estimation Delay Locked Loop

Term	Definition
MOPS	Minimum Operational Performance Standards
MP	Multi-Path
MT	Message Type
MTBO	Mean Time Between Outages
NATMIG	North European ATM Industry Group
NAVAID	Navigation Aid (systems)
NM	Nautical Mile
OCA/H	Obstacle Clearance Altitude/Height
OCS	Obstacle Clearance Surface
OFZ	Obstacle Free Zone
OLS	Obstacle Limitation Surfaces
PACS	Primary Airport Control Stations
PEG	PEGASUS tool; Prototype EGNOS and GBAS Analysis System Using SAPPHIRE (SAPPHIRE is a further abbreviation: Satellite & Air-craft Database Project for System Integrity Research)
PEG TN	PEG Technical Note
PPD	Personal Privacy Device
PR	PseudoRange
PRC	PseudoRange Correction
PRN	Pseudo-Random Noise
PU	Processing Unit
QQ	Quantile-Quantile (plot)
RCSF	Remote Control and Status Function
RCSU	Remote Control and Status Unit
RESA	Runway End Safety Area
RF	Radio Frequency
RFI	RF Interference
RHCP	Right-Hand Circular Polarization

Term	Definition
RINEX	Receiver Independent Exchange Format
RMDT	Remote Maintenance and Data Terminal
RMS	Root Mean Square
RNSS	Radio-Navigation Satellite Services
RR	Reference Receiver
RRC	Range Rate Correction
RRA	Reference Receiver Antenna
RRS	Reference Receiver System
RTCA	Radio Technical Commission for Aeronautics
RTCA/DO	RTCA DOcument
Rx	Receiver
RWY	Runway
SACS	Secondary Airport Control Stations
SARPS	Standards And Recommendation Practices
SCAT-I	Special Category I
SESAR	Single European Sky ATM Research Programme
SESAR Programme	The programme which defines the Research and Development activities and Projects for the SJU.
SJU	SESAR Joint Undertaking
SJU Work Programme	The programme which addresses all activities of the SESAR Joint Undertaking Agency
SV	Satellite Vehicle
TAD	Technical Architecture Description
TCH	Threshold Crossing Height
TCP/IP	Transmission Control Protocol/Internet Protocol
TS	Technical Specification
Tx	Transmitter
UHF	Ultra High Frequency

Term	Definition
UPS	Uninterruptible Power Supply
UTC	Coordinated Universal Time
VDB	VHF Data Broadcast
VHF	Very High Frequency
VHF-COM	VHF COMmunication
VOR	VHF Omnidirectional Range
WGS84	World Geodetic System, dating from 1984
WP	Work Package
xPL	Protection Levels
YUMA	A common format for the GPS almanac

2 GBAS principle and General architecture

2.1 General GBAS Principle

Figure 2-1 illustrates the basic principle of a GBAS ground subsystem (GS) installation. The GBAS GS operates as a differential GNSS installation broadcasting corrective signals to airplanes, that can correct the GNSS signals their GBAS avionics receive. The GBAS GS comprises of several GNSS receivers, sending the GNSS signals to the GBAS GS rack (usually) installed in a shelter somewhere on the airport. The information is treated in a processing unit and sent out to a VDB transmitter antenna, from where the correction signals are sent to the airplanes. A VDB receiver in the ground subsystem will pick up the transmitted radio signal and sends it back to the processing unit for verification. A GBAS GS installation will also comprise one or several control units, e.g. installed in the control tower. On this drawing, only the basic units are presented: Usually the GBAS GS installation will include two to four GNSS receivers and one or more VDB antennas.

The GBAS principle is fundamentally different from ILS in several ways, the two most significant being:

- The approach(es) are imaginary, straight lines in space[1], constructed by two geographical points on the runway (the threshold and the runway end point) setting up the azimuth angle of the approach, and a glide path angle and the threshold crossing height.
- These data are, along with corrections and integrity data for the GPS satellites, transmitted on a digital VDB link to the aircraft (called VDB – VHF Data Broadcast)

GBAS therefore does not suffer from the approach paths being distorted by reflections from objects in the ILS critical and sensitive areas. The digital data are wrapped in checksums, so that the data, which are received by the aircraft, can be received and verified to be accurate and identical to what was transmitted by the ground station. The integrity and accuracy of the approach path can therefore not be affected by interference or reflections on the VDB frequency. The omnidirectional coverage, the potential for ground coverage on the airport, and the possibility to set up trajectories and paths in a digital format, causes GBAS to have potential to cover more phases of flight, other types of trajectories and also taxiing. But note that the SESAR 15.3.6 project scope is limited to precision approach and landing only.

On the other side, the corrections have to be transmitted every 0.5s. This requires special considerations related to loss of messages and time to alarm, in order to meet integrity and continuity requirements.

Also, the flexibility and the potential to cover the entire airport with one station, imposes some challenges on the GBAS especially for GBAS CAT III with the required ground coverage independent of fixed and moving obstacles. It can be quite challenging to guarantee the required field strength in the desired coverage volume. This will be addressed later in this document.

In principle, a GBAS GS installation does not necessarily need to be installed at an airport, but normally the siting restrictions (e.g. security requirements) will dictate so. One GBAS GS may guide air traffic for several runways, as long as the geographical locations meet the siting restrictions that apply to the individual categories of runways being served.

Since the GBAS Ground Station can transmit corrections, integrity information and approach paths that apply to all approaches on an airport on a single frequency, it utilizes the VHF frequency assigned to it in a far more efficient way than ILS. In comparison, ILS requires one VHF and one UHF frequency for each approach. This is an important benefit in areas with frequency congestion problems in this band. Whereas GBAS can cover all approaches, both azimuth and elevation with

[1] The described way defines straight in final approach segments for precision approach mode that a GBAS serves. The GBAS principle is capable to provide flight path information for advanced approach operations as well as a service for differentially corrected positions. These are out of scope here.

a single 25 kHz frequency band assignment within the band 108 to 117.975 MHz, a single localizer requires 50 kHz in the band 108.10 to 111.95 MHz.

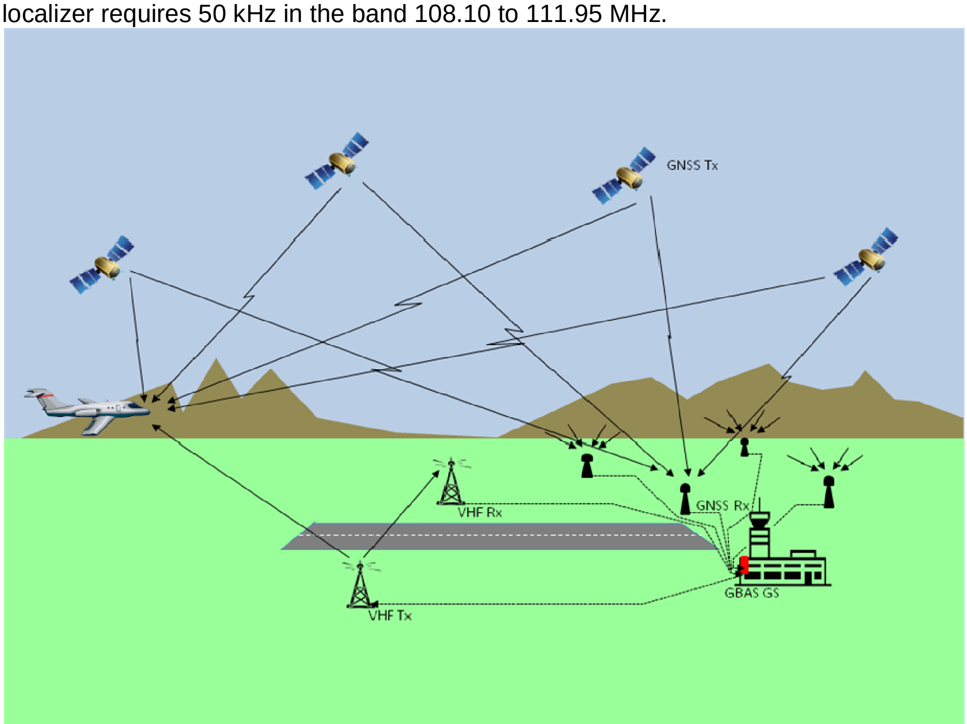


Figure 2-1: Basic GBAS Architecture

Documents proposing GBAS GS architectures on a similar level, is RTCA DO-245A [3] and ED-144 [2]. ED-114 [1] and the FAA Non-Fed spec [4] propose architecture on a more detailed level.

2.2 General GBAS Ground Station Architecture

A GBAS GS comprises the following elements:
- GNSS receivers & antennas
- VDB transmitter, receiver and antennas (possibly including VDB receive antennas)
- Control, operation and maintenance panels
- The main GBAS cabinet, usually mounted in an in-door rack, including:
    - o GNSS receiver subsystem
    - o Processing unit
    - o VDB transmitter unit
    - o VDB receiver unit
    - o Control, operation and maintenance units, including monitors

Depending on the chosen architecture, some of the elements listed under the main cabinet may be located externally.

A GBAS GS installation will include several GNSS antennas in order to increase accuracy, availability and assure integrity. 15.3.6 D03 [6] states that the number of required receivers for GAST D is slightly unclear, but the assumption is that four receivers are required to be installed, whereas the station can operate with down to 3 receivers. The FAA Siting order for GBAS to serve approach operations down to CAT I (i.e. GAST D is not included) [7] requires a minimum of four installed receivers. The GNSS receivers are part of the ground system, and may be an integrated part of the GS cabinet, or co-located with the antennas or in their proximity. The ICAO NSP paper [18] concludes, based on assessment of a general monitor, that it is possible to operate on 3, possibly even down to 2 receivers for a limited duration. This result needs to be assessed further, considering specific monitors such as the ionospheric gradient monitor. More than 4 receivers could be considered. This is not covered in any standard, but could be beneficial for the purpose of robustness, in particular against RFI. However, this will be a significant cost driver, both in terms of equipment and installation costs. Therefore, in this document, four receivers are considered the maximum.

The VDB transmitter is in charge of transmitting a broadcast signal with GNSS correction signals, ground station information and final approach path data to approaching aircrafts. This requires line of sight to all approaches, a certain signal strength to ensure the defined coverage range, and eventually measures taken to reduce VDB multipath. It may be possible to implement a GBAS station without a VDB receiver unit, however, ICAO SARPs [9] appendix B, 3.6.7.3.1.1*VHF data broadcast monitoring* requires the data broadcast transmissions to be monitored, and to cease transmission upon disagreement between the transmitted application data and the application data derived or stored by the monitoring system prior to transmission. Note also RTCA DO-245 [3] 3.2.5.6.1: "The ground subsystem shall monitor all data broadcast transmissions". Therefore, for practical purposes, most GBAS architectures will include a VDB receiver, and at least one receiver is assumed in the general architecture presented in this document. The receiver is also used to monitor the signal strength and the correct assignment to time slots.

The processing unit will perform the PRC computation, GBAS message formatting and monitoring required to ensure the integrity, continuity and availability specified in [11] for a GBAS GS.

The user interface typically consists of the following items:
- A Local Control Function for basic controls such as putting the station into maintenance, resetting, turning the VDB signal on/off, and for display of basic status of the ground station
- A local Maintenance Data Terminal (MDT), for configuration, diagnostics and detailed status
- A Remote Control and Status Function: For basic control, status and high level diagnostics, typically installed in the equipment room
- An ATC Control and Status Function: Basic status and optionally controls provided in the tower.
- A Remote Maintenance Data Terminal providing diagnostics and detailed status of the system. It is also possible to envisage control and configuration of the ground station from this terminal, however; in this case, safety and security issues have to be carefully considered.

All these units have an interface to the processing unit, either directly or through other units. The type of interface depends on the distance and the type of media/interfaces typically provided.

Differences between the CAT I and the CAT II/III requirements for a GBAS system may have impacts on the ground station architecture. We will identify these differences and possible consequences for the architecture.

One of the main differences is of course the decision heights and the runway visual ranges, defined as 60m for the minimum decision height and either a visibility not less than 800m or a visual range not less than 550m for CAT I. For CAT II the numbers are 30m and 300m respectively, and for CAT III down to zero for both depending on the sub-categories A, B and C. These differences are reflected in the requirements to integrity and continuity. The integrity requirement for CAT I is $2 \cdot 10^{-7}$ per approach, whereas it is $1 \cdot 10^{-9}$ per approach for internal faults and $1.0 \cdot 10^{-9}$ per approach for failure to bound satellite errors for CAT III. The requirement on continuity is $8 \cdot 10^{-6}$ per 15s for CAT I, and $2 \cdot 10^{-6}$ per 15s for CAT III with an additional requirement on $2 \cdot 10^{-7}$ per 15s for exclusion of individual satellites. The difference in the stringency of the integrity and continuity requirements leads to an architecture with higher focus on the reliability of the reception of the GNSS signals, and the transmission of the correction signals. As described above, the number of GNSS receivers in a GAST D ground station is driven by the P_{md} (Probability of missed detection) and P_{FA} (Probability of False Alarm) requirements, and the corresponding monitoring schemes. Preliminary investigations show that 4 receivers may be sufficient to meet the GAST D requirements. A ground station supporting CAT II/III system is also likely to have more than one VDB transmitter, although no specific requirements to this exists. Figure 2-2 below illustrates a general ground station architecture.

Based on the integrity requirements, certain monitors have to be implemented in the ground subsystem. Some of these monitors will impose requirements on the siting of the GNSS antennas.

The LOCA (Local Object Consideration Area) is to a large extent defined by the antenna's susceptibility to multipath and the receiver characteristics. The definition of the LOCA is elaborated in the FAA document Siting Criteria for Ground Based Augmentation System (GBAS) [7]. It recommends that no fixed structures are present within the LOCA. However, this will rarely be possible. Therefore, the impact of structures inside the LOCA has to be taken into account and compensated for in the transmitted σ_{pr_gnd} (refer to section 4.2.3.1).

In addition, it is important to avoid multipath which is correlated between the GNSS reference receivers. Due to that, the distance between GNSS reference receivers should be at least 50 m, and any structures within the LOCA must be considered for potential correlated multipath. In order to ensure that correlated multipath is not present, a dual-frequency logging campaign should be carried out. This can be done during siting if correlated multipath is suspected or during site acceptance if one is relatively confident that the level of correlated multipath is acceptable.

The ionospheric gradient monitor used in the ground station will put restrictions on antenna separation. Currently, two monitor types are being discussed, the "Absolute Slant Ionosphere Gradient Monitor", using short baselines, and the long baseline monitor, referred to as IFM – Ionospheric Field Monitor.

Siting restrictions are highly dependent on choice of ionospheric monitors. At the time of writing, both monitor types are being investigated. The absolute gradient monitor has the advantage that it requires relatively short baselines between the antennas (in the order of 50 to 300 m) and therefore normally will be less costly to install. However, it requires specific geometries between the antennae, and therefore may be difficult to site on some airports. In addition, this monitor requires very low noise measurements. It has still not been confirmed that these noise levels are achievable in practice on a stable basis, for instance under high wind conditions. The monitor's performance under all typical environmental conditions, such as e.g. phase scintillations, must be investigated to determine the feasibility of the monitor [17].

The IFM (Ionospheric Field Monitor) will be located at a different site than the ground station itself. For practical reasons it needs to be located inside the airport security fence. This is for security reasons and because of the difficulties an airport will have in acquiring and maintaining properties outside the airport. There could be more than one monitor, e.g. one near each of the two most remote thresholds. The monitors need to communicate back to the ground station the measurements performed, in order for them to be synchronised with measurements performed there. Therefore, some infrastructure needs to be in place for this purpose, which is the most important argument against this monitor. However, it can be argued that all CAT III ILS's in the world uses far field monitors on all CAT III thresholds, so this type of infrastructure could be established also for other CAT III landing systems as well.

RFI (Radio Frequency Interference) considerations may impact siting as well. Generally, public areas such as highways, parking lots etc. are particularly likely sources of RFI as PPDs (Personal Privacy Devices) in the form of GPS jammers are occasionally used in cars/trucks. The range of these devices is normally limited. Therefore, the likelihood of a PPD in a car jamming the GBAS station can be reduced by moving the station away from public areas, if possible.

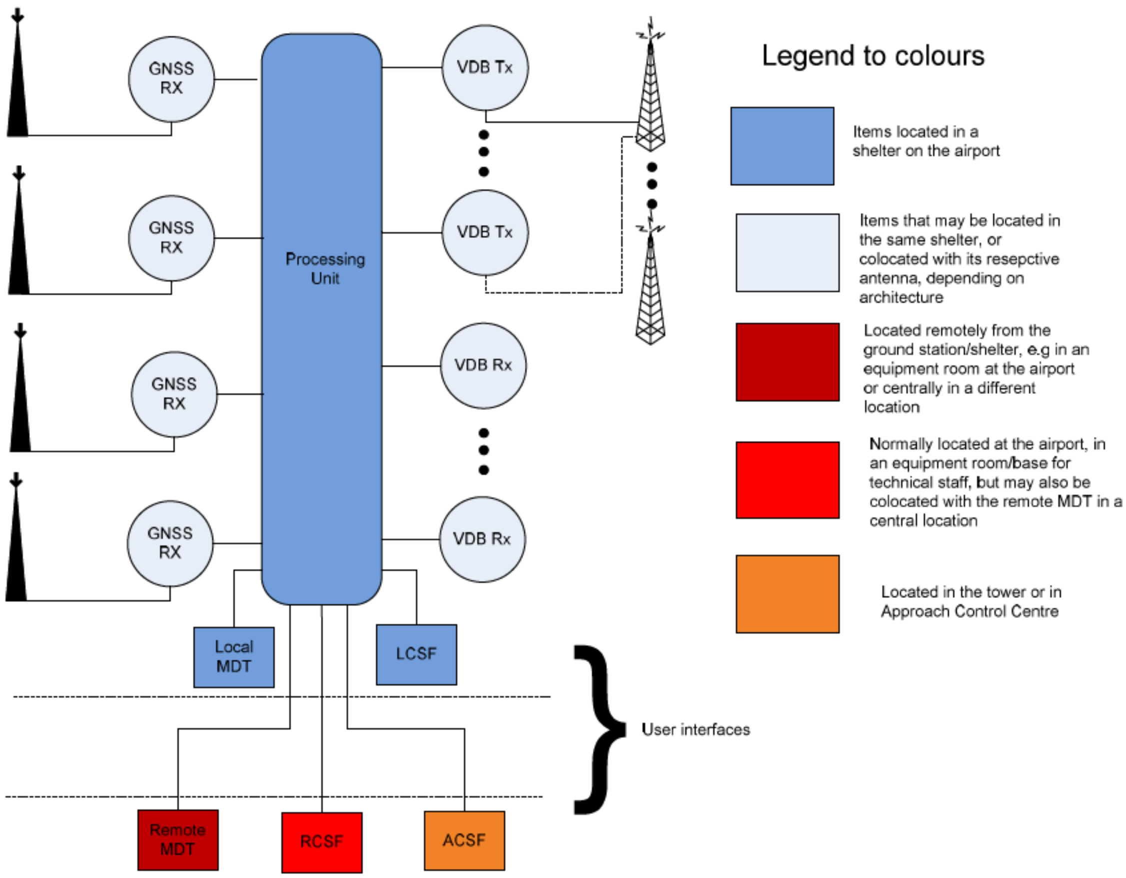


Figure 2-2: General GBAS Architecture

The main differences in requirements from CAT I to CAT II/III affecting the GBAS architecture, are the integrity and the continuity requirements. The stricter integrity requirements may impose stricter requirements on GNSS antennae and potentially also receivers, in that the noise and multipath levels must be minimised in order to define the necessary detection thresholds for monitors, without violating the probability of false alarm requirements.

The most restricting factors with respect to the continuity requirements are the probability of false alarm of the monitors, and the constellation. However, redundancy of the GNSS receiver and VDB transmitter is considered in the general architecture as it may be required to meet the continuity requirements. In addition, many customers require a fully redundant system in order to avoid single point of failure. As shown in the figure above, additional VDB transmitters may be connected to the same antenna in a dual-redundant configuration, or to separate antennas to increase coverage, depending on architecture and the requirements of the operator.

The need for higher precision for CAT II, and especially CAT III landings, together with the more stringent requirements on integrity and continuity, also means that eventual system or satellite errors must be monitored and followed up more closely. The GBAS community has come up with several threat models, in order to describe the error sources that need to be taken into account. These are;

- Excessive Acceleration
- Ephemeris error
- Ionospheric or tropospheric differential errors
- Code carrier divergence
- Signal deformation

These aspects are covered in depth in 15.3.6 deliverable D03 [6]. In addition, threats identified for the GAST C (CAT I) must be taken into account, such as the impact of RFI and noise (low signal-to-noise level).

Detection, and potentially correction, of these errors require monitors in the ground system. These monitors are also implemented in a CAT I system, but the increased CAT II/III integrity requirements impose stricter requirements on the probability of missed detection of each monitor. The implementation of monitors will have an impact on the software architecture, and this may also lead to changes in the hardware architecture if an upgrade of components, or even new components are found necessary. Siting restrictions may also change.

3 Airport architecture

3.1 General airport architecture

Aerodromes design recommendations are covered by ICAO Annex 14 and FAA AC 150/5300-13. These documents are focused on: runways, taxiways, apron and NAVAID areas design, including their security areas. Nevertheless, airports have other facilities: terminals, hangars, control tower, etc. which have to meet the security areas and impact significantly the airport layout.

These areas are defined in ICAO Annex 14 [21]:

- Runway.

  A defined rectangular area on a land aerodrome prepared for the landing and take-off of aircraft.

- Stopway.

  A defined rectangular area on the ground at the end of take-off run available prepared as a suitable area in which an aircraft can be stopped in the case of an abandoned take off.

- Taxiway.

  A defined path on a land aerodrome established for the taxiing of aircraft and intended to provide a link between one part of the aerodrome and another.

- Apron.

  A defined area, on a land aerodrome, intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fuelling, parking or maintenance

- Obstacle free zone (OFZ).

  The airspace above the inner approach surface, inner transitional surfaces, and balked landing surface and that portion of the strip bounded by these surfaces, which is not penetrated by any fixed obstacle other than a low-mass and frangibly mounted one required for air navigation purposes.

  Obstacles limitation surfaces (OLS) define the airspace around aerodromes to be maintained free from obstacles so as to permit the intended aeroplane operations at the aerodromes to be conducted safely and to prevent the aerodromes from becoming unusable by the growth of obstacles around the aerodromes. Dimensions and slopes of OLS define the limits to which objects may project into the airspace. OLS for Precision Approach runways category II/III are provided in Appendix A to this document.

- Runway end safety area (RESA).

  An area symmetrical about the extended runway centre line and adjacent to the end of the strip primarily intended to reduce the risk of damage to an aeroplane undershooting or overrunning the runway.

3.2 Airport facilities and infrastructure

This section explains the main points of an airport's infrastructure that might affect the siting of a GBAS station. The facilities analyzed are only the configuration of runways and terminals, which are the most restricting to perform the siting. Nevertheless, special consideration should be also given to airport specific issues such as fences, snow depots and cable ducts.

3.2.1 Runway configuration

Airport layout is meant to assist pilots in easily recognizing runways from the air and to taxi safely from the runway to the gate. From runway numbers and painted stripes to airport and runway lights and signs, national and international regulation is applied.

There are 4 basic runway configurations [22]:

a) Single runway

It is one runway optimally positioned for prevailing winds, noise, land use and other determining factors. During IFR (instrument flight rules) conditions, it would accommodate between 50 to 60 operations per hour depending on the mix of traffic and navigational aids available at that airport.

b) Parallel runways

They are at least two runways with the same geographical orientation. There are 4 types of parallel runways: close parallel, intermediate parallel, far parallel and dual-line runways. These are named according to how closely they are placed next to each other.

c) Open-V runways

Two runways that diverge from different directions but do NOT intersect form a shape that looks like an "open-V" are called open-V runways.

d) Intersecting runways

Two or more runways that cross each other.

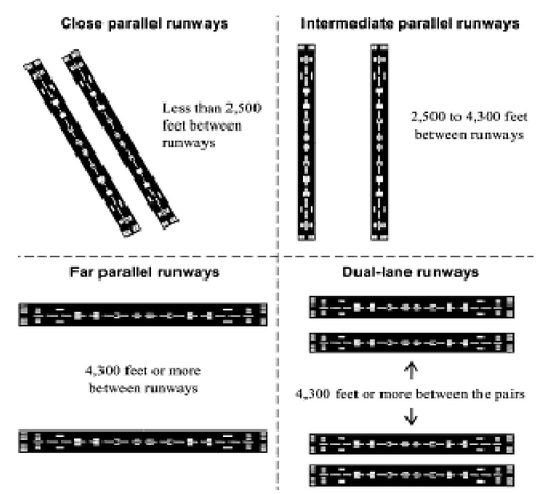


Figure 3-1: Parallel runways

(Courtesy of [22], Figure 8).

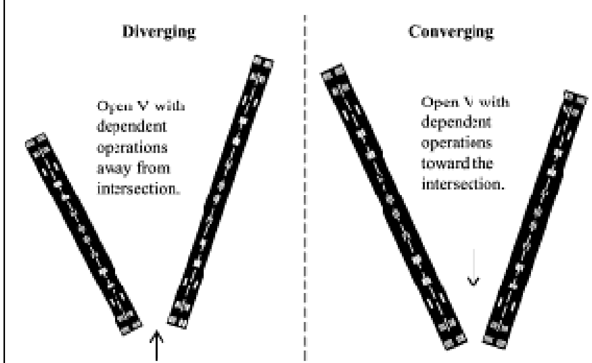


Figure 3-2: V-Shape runways

(Courtesy of [22], Figure 9).

3.2.2 Taxiway configuration

Because of the total length taxiways are the second major component of airfield. Basically, there are four different taxiway configurations [22]:

a) Parallel taxiways run parallel to the runway.

b) Entrance taxiways lead to one end of the runway and are used by departing aircraft to reach their take-off position.

c) Bypass taxiways allow aircraft to bypass other aircraft on their way to the runway,

d) Exit taxiways and express taxiways allow the aircraft to leave the runway.

3.2.3 Terminal configuration

In addition to runways, terminals are one of the main facilities that impact on airport's design. The five basic types of terminals are [22]:

a) Simple terminal

This configuration consists of one building holding a common ticketing and waiting area with several exits leading to a small aircraft parking apron for boarding. This is used at mainly small aircraft airports and some older large airports.

b) Linear terminal/ Curvilinear terminal

This is simply an extension of the simple terminal concept providing more gates.

c) Pier finger terminal

Gate concourses were added to the simple terminal building designs. A concourse is actually defined as an open space where paths meet. Aircraft are parked in the "finger" slots or gates for boarding.

d) Pier satellite terminal/ Remote satellite terminal

This configuration involves a single terminal connected to numerous concourses that lead to one or more satellite structures. At the end of each concourse the aircraft are parked in a cluster. People-mover systems are employed in these settings to reduce walking distances.

e) Mobile lounge or transporter terminal (remote aircraft parking concept)

Passengers are transported to and from the building to the parked airplane. Airplanes are parked at gates placed along parallel rows. Several sets of parallel parking rows can be created as increased traffic deems such expansion necessary. With this concept, aircraft can be parked remotely from the terminal buildings.

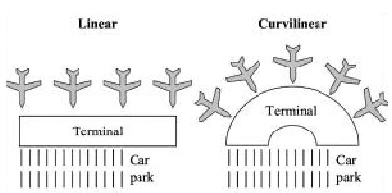


Figure 3-3: Linear/Curvilinear terminal

(Courtesy of [22], Figure 16).

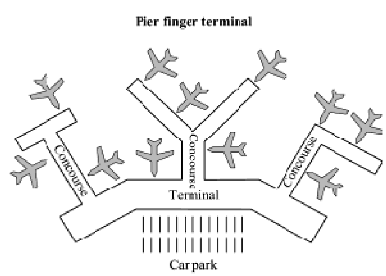


Figure 3-4: Pier finger terminal

(Courtesy of [22], Figure 16).

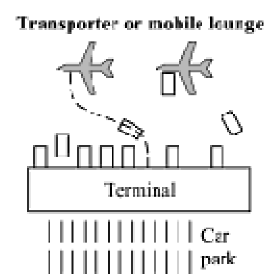


Figure 3-5: Mobile lounge

(Courtesy of [22], Figure 9).

3.2.4 Examples of airport architecture

Firstly the main elements of airport configuration (i.e. runway and terminal) have been described above from a theoretical point of view. This chapter describes the configuration of real airports in order to extract some trends that could affect the installation of GBAS stations.

The configuration of four Spanish airports has been analyzed, and the selection is based on their number of operations: Madrid (LEMD), Barcelona (LEBL), Palma (LEPA) and Málaga (LEMG). Other Spanish airports with ILS CAT II/III installation have only one runway and they are not analyzed due to its simplicity. On the other hand, Frankfurt (EDDF) and Toulouse (LFBO) airports layout are also included because they are the scenarios where GBAS GAST-D station prototypes will be installed.

In the figures below, facilities are highlighted from the AIP airport layout. Runways are highlighted with red dashed rectangles, terminals with green dot rectangles and hangars and other significant buildings with orange dot.

As it is observed in following figures, Frankfurt, Toulouse and main Spanish airports have parallel runways as the most common runway configuration. In addition linear and curvilinear terminal or pier finger terminal are also commonly used as terminal configuration. Considering hangars and any other building, they are usually located close to terminals or surrounding the runways.

Besides, airports using parallel or open-V runways usually have their terminals buildings located between runways. This is an important issue to be considered during GBAS station siting, especially concerning the coverage of VDB antenna along runways.

The conclusions of this analysis, performed only at main Spanish airports, are expected to be general enough to cover any other airport.

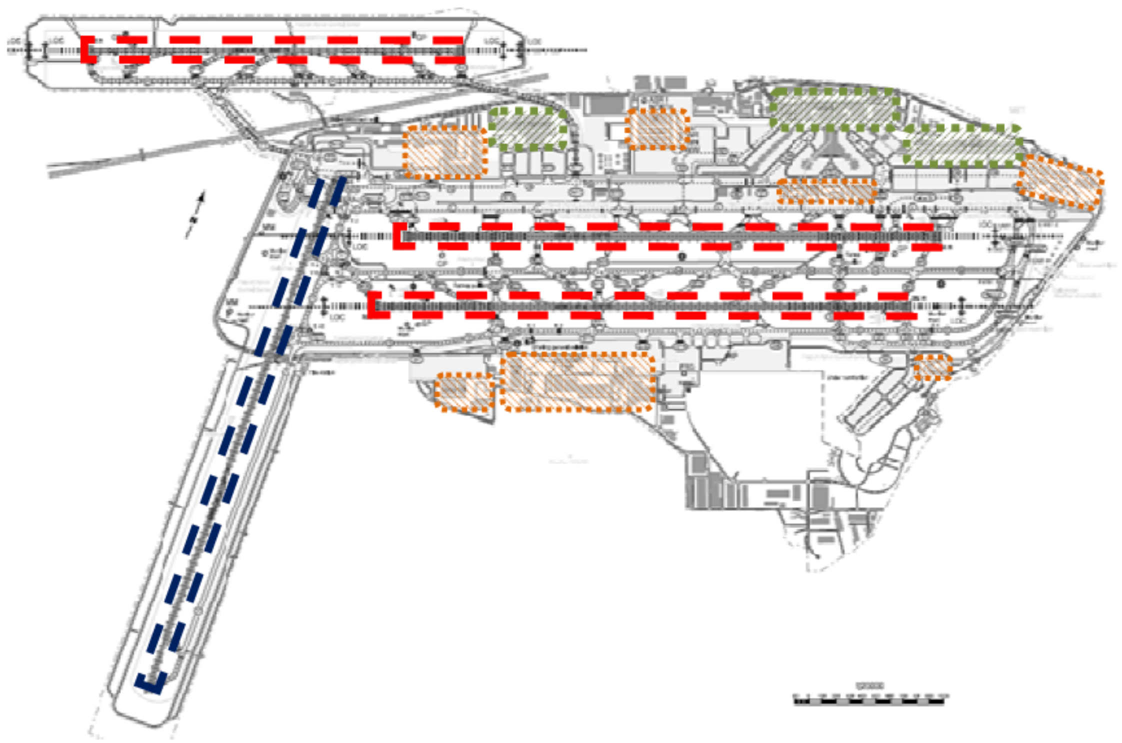


Figure 3-6: Frankfurt airport layout (EDDF)

Note that for Frankfurt airport, RWY 18 (marked in blue) is only used for take-off.

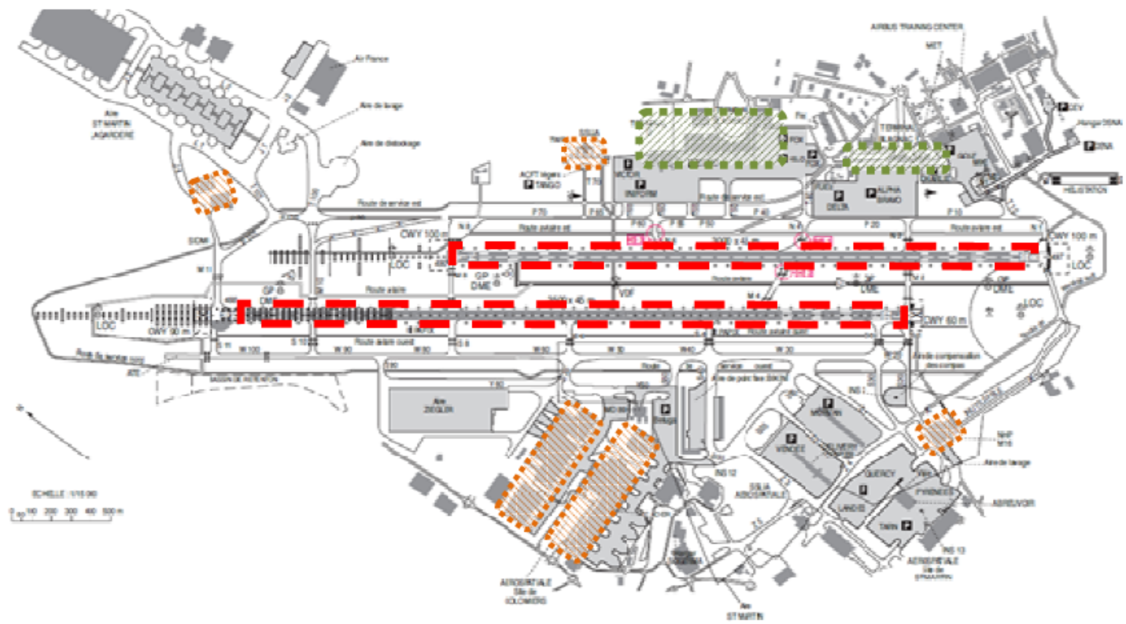


Figure 3-7: Toulouse airport layout (LFBO)

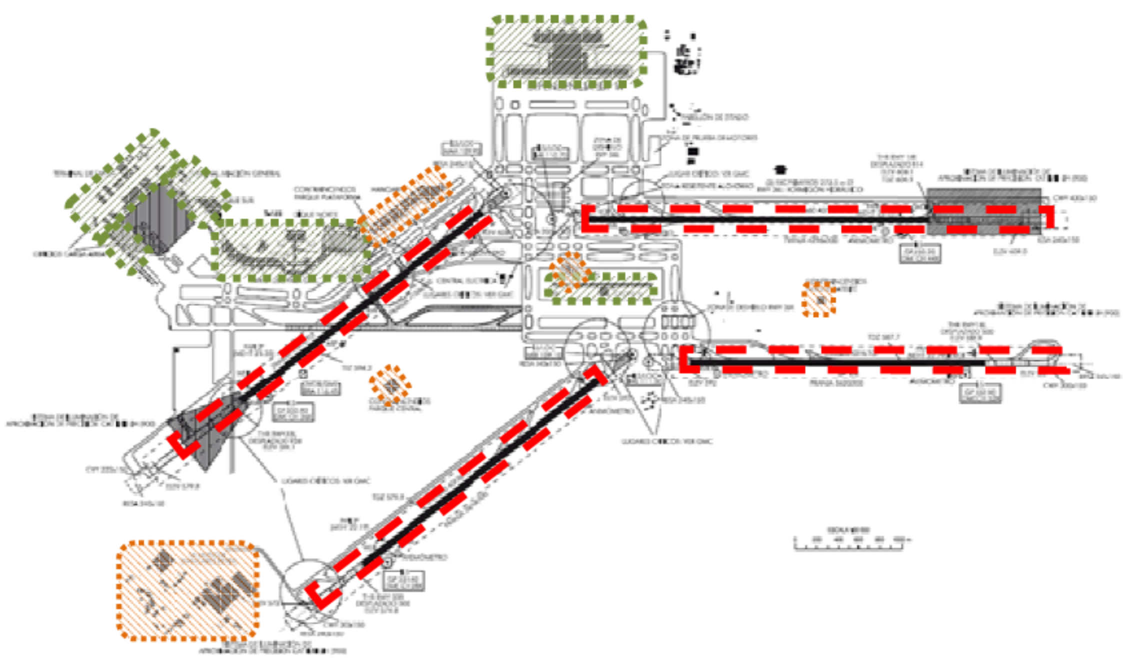


Figure 3-8: Madrid airport layout (LEMD)

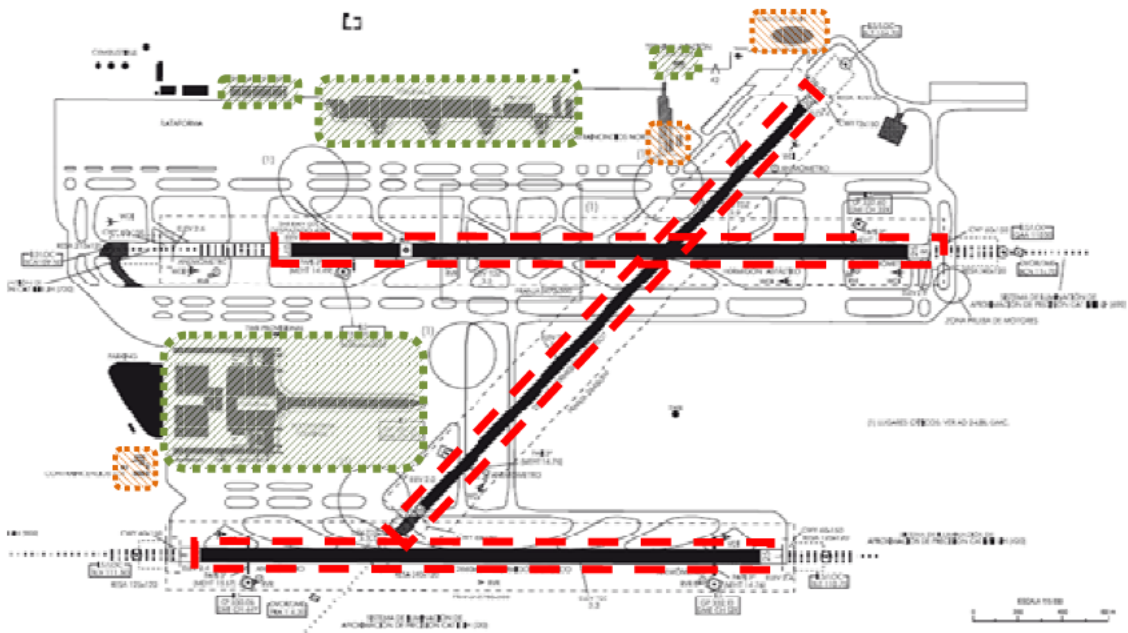


Figure 3-9: Barcelona airport layout (LEBL)

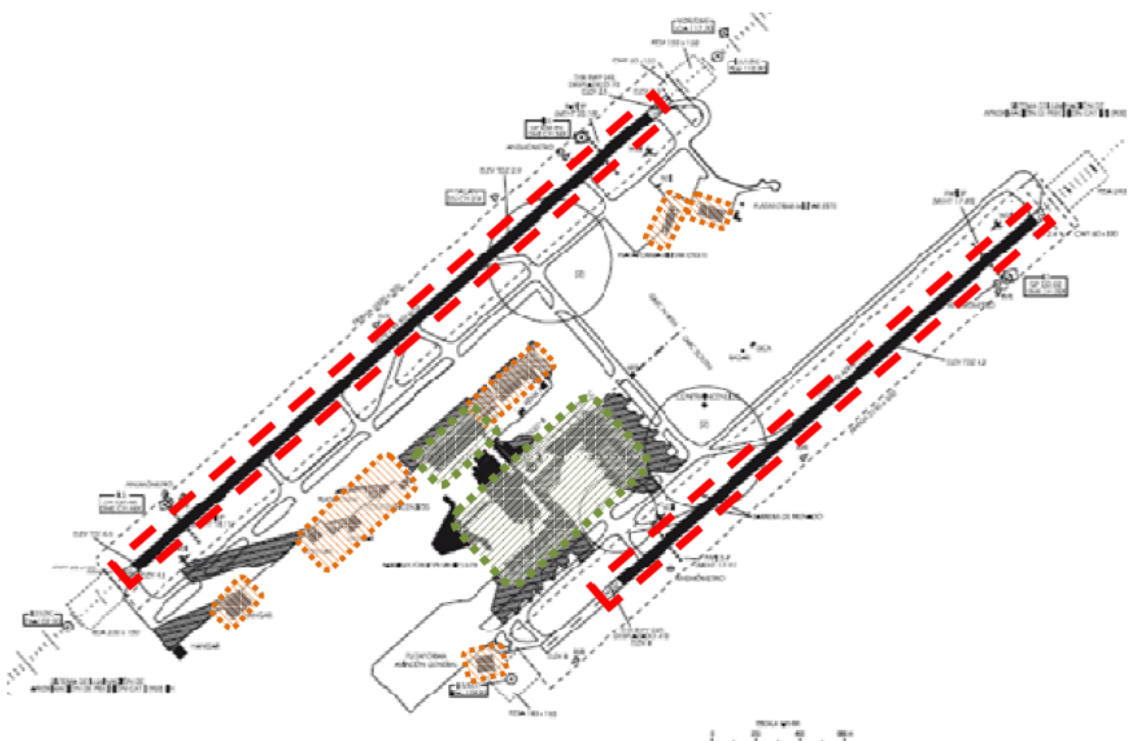


Figure 3-10: Palma de Mallorca airport layout (LEPA)

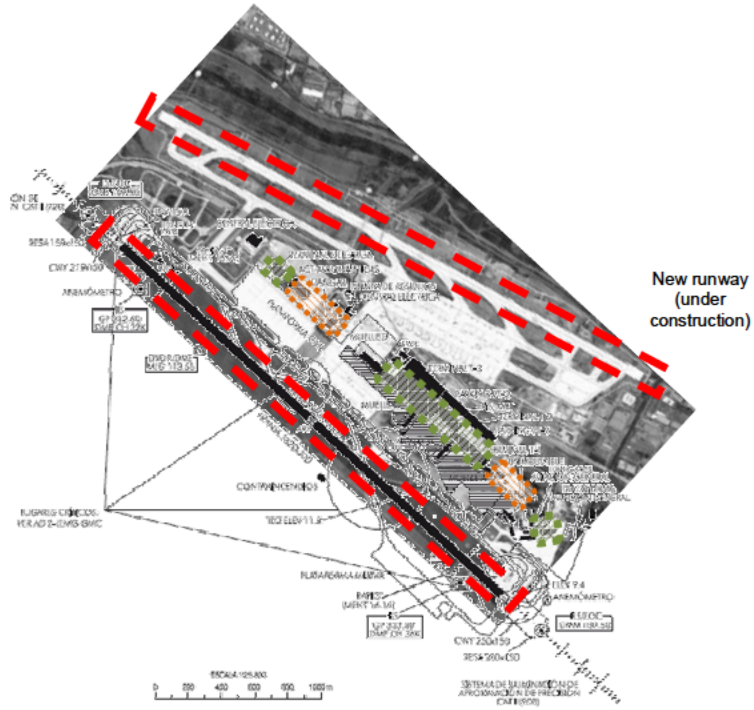


Figure 3-11: Málaga airport layout (LEMG)

3.3 Expected trends in the future

It is a challenge to develop equipment that shall not only just be commercialized in some years, but also last for years, or even decades, after that. It is therefore of interest to try to foresee some of the trends that are likely to impact the environment in which the GBAS ground system is to operate. We have made an attempt in the following to list some of the trends we see. This list is by nature non-exhaustive and characterized by a high degree of uncertainty. Some of the elements are likely to complicate matters, like increased traffic, whereas others will most probably facilitate the introduction of new types of equipment like GBAS, like upgraded infrastructures with optical fibre connections between ground subsystems.

3.3.1 Increased air traffic

One of the advantages of the GBAS system is actually exactly to be able to handle more traffic, with less equipment. As one ILS installation operates only one runway end, one GBAS installation may operate several (all) runways on an airport. However, this does not go without proper dimensioning of the system. Coverage on all runway ends that are to be served must be provided, and as the number of aircraft movements dependent on GBAS increases, the availability requirements may become stricter. The result of this may be that for large airports, more than one GBAS station may be required in the future. Also, as the constellation is a driving factor for the availability, the dependency on a single constellation may become a limiting factor with respect to which degree one will rely solely on GBAS for precision approach.

3.3.2 Constructions closer to operational areas

As traffic increases, the airports need to expand to cope with the increased traffic. In many cases, the available real estate for expansion is limited or non-existing, as airports (in particular large airports with increasing traffic) are generally located in densely populated areas. Therefore, expansions are often required to take place within the area already allocated to the airport, causing the density of infrastructure to increase. This raises two issues which are related to GBAS:

- The areas where a GBAS ground station could be located are being reduced. Since GBAS has no dedicated areas, like ILS, it is difficult to protect an area against building with the argument that it should be reserved for a future GBAS ground station.
- Hangars, terminals and public areas like roads come closer to operational areas like runways. This may cause the problems of jamming and spoofing (including repeaters) to increase.

3.3.3 Middle marker no longer included

The Middle markers indicate the CAT I missed approach point, i.e. the point at which the pilot should see the runway which is about 1100m from the threshold. According to ICAO, middle markers are not mandatory where a DME is available. The ICAO requirement is implemented slightly different from country to country, but in general, the tendency is that it is becoming less common to have a middle marker installed. Due to this, the land previously allocated to the middle marker is in many cases no longer inside the airport perimeter. This causes the land available for siting a GBAS ground station to shrink.

3.3.4 Using ILS localizer far field monitor location

ILS localizer far field monitors (FFM) are used to monitor mainly the ILS course alignment. They are generally considered essential for Category III operations. For course line monitoring, the FFM antenna is usually positioned along the extended runway centre line.
The exact position is site dependent but for practical reasons the FFM is generally co-located with the ILS middle marker (when exists see 3.3.3 above) or with the ILS localizer serving the opposite runway direction.

Therefore, there is a possibility to use the existing locations of the ILS localizer FFM for GBAS monitoring purposes. For example, some ionospheric gradient monitor architecture may use this location to observe the GNSS signal on the extended runway centre line. However, it has to be noted that the GNSS signal received at this location may suffer short-term masking effects caused by aircraft flying directly overhead. Means must be adopted to minimize such temporary effects.

3.3.5 GNSS repeaters and jammers

GNSS repeaters are used for indoor navigation and for aircraft maintenance, e.g. alignment of inertial platforms. Regulations exist to prevent this type of installations from causing a problem to other navigators, but the regulations are sometimes being violated, causing problems for users of GBAS.

Some road pricing and fleet management systems use GPS, and in order to avoid being tracked by these types of systems, some drivers install GPS jammers in their cars. These jammers will in some cases have sufficient power also to impact a GBAS system (as well as other GPS based approach and landing systems).

Jammers and repeaters tend to be an increasing problem. Better enforcement of the regulations, and in some cases, improvement of the regulations, may reduce the problems, but the manufacturers, owners and operators of satellite based approach and landing systems need to address the impacts of such interference. Locating GBAS installations as far away from public areas and hangars as possible could be one mitigation that needs to be looked at. However, this is not considered to be sufficient as the emitted power may in some cases exceed the levels that may be mitigated in this way, and also, on some airports, other siting restrictions and lack of available space may prevent this. Also, since the possibilities for mitigating these effects in the airborne equipment are limited, strong regulations and enforcement of these is likely to be the most important mitigation against interference.

3.3.6 Communication lines

Upgrades from copper wires to optical fibres often take more time than one could expect. The technology is there, and has been so for a couple of decades, but it all comes down to the expenses and complexity linked to the actual digging of ditches, usually with the expectation of un-interrupted services. But, upgrades are taking place, and all new installations will supposedly be done with optical fibre cabling.

The cables of interest are the cables to the remote control panel(s), MDT, GPS reference antenna cables, GPS reference receiver cables, and VDB transmitter cables or VDB transmitter antenna cables. The choices depend on how much of the processing that will be installed remotely (data vs. RF transmission cables). Use of optical fibre cables is of interest for any data transmission. The most obvious benefit of optical fibres is that the signal power loss is minimal, and therefore the limitations for possible distances between different types of equipment vanish in practice. This is important, as the requirements for installation of GBAS antennas, both receivers and transmitters, lead to minimum distances between antennas being defined, and the airport topography/architecture (real estate, fences, buildings, hilltops, water surfaces, runways, maintenance work etc.) may itself impose limitations as to where you may install an antenna. Secondary benefits are invulnerability to lightning, lower noise figures, higher bandwidth etc. One issue that has to be carefully considered is potential delays related to conversion between the different communication media.

The installation of the GPS antennas must ensure that there are no correlated multipath errors between the antennas, as any common-mode errors may violate the integrity monitoring requirement. Hence, a minimum distance between the GPS antennas is required. The GPS receiver may be co-located with the GPS receiver antenna, in which case the RF cable may be quite short, whereas the data cable connecting the receiver to the rest of the GBAS GS, the processing unit (PU), then will be the longer. Where the receiver is co-located with the GBAS PU, the RF cable length between the GPS antenna is limited by cable losses.

There are also two possible locations for the VDB transmitter and receiver, either collocated with the GBAS PU, and thus connected to the VDB antennas via RF cables, or collocated with the antenna and linked to the GBAS PU via data cables.

If the processors are collocated with the antennas, GPS or VDB, there will be a need for sheltering, as this equipment is usually not designed for outdoor operation. Also, there will then be a need for power supply at the antenna site, and synchronization with the ground station must be carefully considered in order to meet the requirements for out-of-slot transmission.

Finally, connections to remote control panels will usually be of the type data connections.

The data connections may be improved by using fibre optics instead of data communication cables such as RS232, RS422, or RS485. One would expect that any new cables being installed are strong candidates for the optical fibre choice. Replacing copper cables with optical fibres will increase the number of options for the GBAS architecture. The installation will be easier to optimize depending on the particular features of any particular airport, in addition to enhanced operational conditions linked to the increased bandwidth and/or the reduced noise.

We take as an example the possibility of remote location of the GPS receiver. RS232 is actually not an option for data rates such as those we talk about for GPS signals. E.g. the CMA4048 GPS receiver uses 115kbps, which is too high for RS232 even for distances on the order of a couple of meters. The maximum length of an RS422 or RS485 will be about 1km. Optical fibres will in practice cover several kilometres, but fibre connections are not default in standard equipment today. Therefore, use of optical fibres will require additional hardware devices for multiplexing signals as additional information (e.g. environmental) than just the GPS signal, is usually wanted from remote locations, or several fibres have to be used. Implementing additional hardware implies additional delay for time critical signals.

3.3.7 Airport staffing

It appears to be a tendency with several ANSPs that the technical staff is being reduced and centralized. In some countries, there is a tendency to move against a centralized monitoring facility having the overview of installations and facilities over a large area. These then have local technicians on call who they can contact in case of a fault. There may be many reasons not to keep staff permanently on an airport, for instance for remote airports with little traffic. In these situations, the status of the equipment is usually being monitored by the ATC controller or AFIS operator, who will call a technician covering one or more airports for the repair of the problem.

It could be beneficial to consider such a development in the architecture and technical solution of a ground station. A possibility of remote monitoring and download of logged data will be required in case of central remote monitoring centres. Remote control and configuration from these central sites could be a possibility from a technical point of view, but the safety and security aspects of such a solution must be carefully considered so that the integrity and continuity requirements of the ground station cannot be violated. Also, the controls and the information being displayed in the tower may need to be considered in the light of the availability of technical personnel on the airport.

4 Mutual influence between siting and architecture

A general picture on an architecture for a GBAS ground station may be found in ED-114 [1], [2], and will be updated in coming ED-114A document. An introduction video to GBAS architecture has been made by Eurocontrol, and is called GBAS_demo (1).

4.1 General Siting considerations

This section gives an overview of general criteria for siting and the relationship to the various architectural elements. The key factors and recommendations elaborated by the ANSPs in the Siting discussion paper [5] are considered. The scope for the site survey process is to find the site with acceptable system availability and sufficient VHF coverage taking practical issues such as accessibility into account.

In general, the siting process consists of the following steps:

-Site selection
-Site Qualification
-Installation
-Site Acceptance

The procedure related to siting is addressed in detail in section 6. Here, the physical aspects and criteria to take into account are addressed. This section also looks at how the siting criteria affect the architecture and vice-versa.

In order to identify potential candidate sites, it is necessary to have an overview of the main siting criteria, some of which are general, and some of which are manufacturer specific.

The general ones are:

ID	Siting Criteria	Applicable Architectural element
S1	Security aspects: The ground station and at least the GNSS receiver antennae must be installed in secure areas, inside the airport fence.	GNSS Shelter/Processing unit VDB
S2	Airport siting considerations, considerations related to obstacle limitation surfaces	GNSS Shelter/Processing unit VDB
S3	Coverage volume: o The minimum field strength requirement needs to be addressed. The radiated signal is as unobstructed as possible, ideally there should be line of sight to all operational areas. LOCA should be respected. o The VDB antenna is not located more than 3NM from every runway threshold o The maximum field strength requirement needs to be addressed, restricting how close to operational areas the VDB transmitter can be located. In area where GBAS services are not used the airborne receiver burn-out requirement can be considered to reduce the necessary separation.	VDB
S4	Maximum distance from GBAS reference point to any threshold served by the station is 5km (GAST D	GNSS

	specific) in order to mitigate ionospheric anomalies.	
S5	Horizon/elevation mask: obstacles above 3 degrees should be avoided for the GNSS antennas if possible, as shadowing may impact both availability and continuity. The siting area should be predominantly flat and with low/limited vegetation	GNSS
S6	Reflecting surfaces in the vicinity of the GNSS antennas: Multipath and in particular correlated multipath should be avoided. LOCA should be respected. Water surfaces or standing water on the ground should be avoided in this area.	GNSS
S7	Minimum separation and specific geometric arrangement between GNSS RRAs: related to the ionosphere gradient monitoring performance	GNSS
S8	Climate conditions and seasonal variations: o Areas where snow tends to build up should be avoided. o Areas used for snow deposits must be avoided, or these must be moved. o Minimum antenna height is determined by the maximum snow depth. o Possible flooding must be taken into account	GNSS (VDB)
S9	Any potential airport expansion/modification plans	General
S10	Possible reuse of existing infrastructure	General
S11	Distance to public areas (related to RFI aspects)	GNSS

Table 1: General Siting Restrictions

The manufacturer specific siting criteria are determined by the architecture and the physical implementation of the specific ground station. For each manufacturer, some separation distances must be determined (some may be N/A for some manufacturers). These are depicted in Figure 4-1 below.

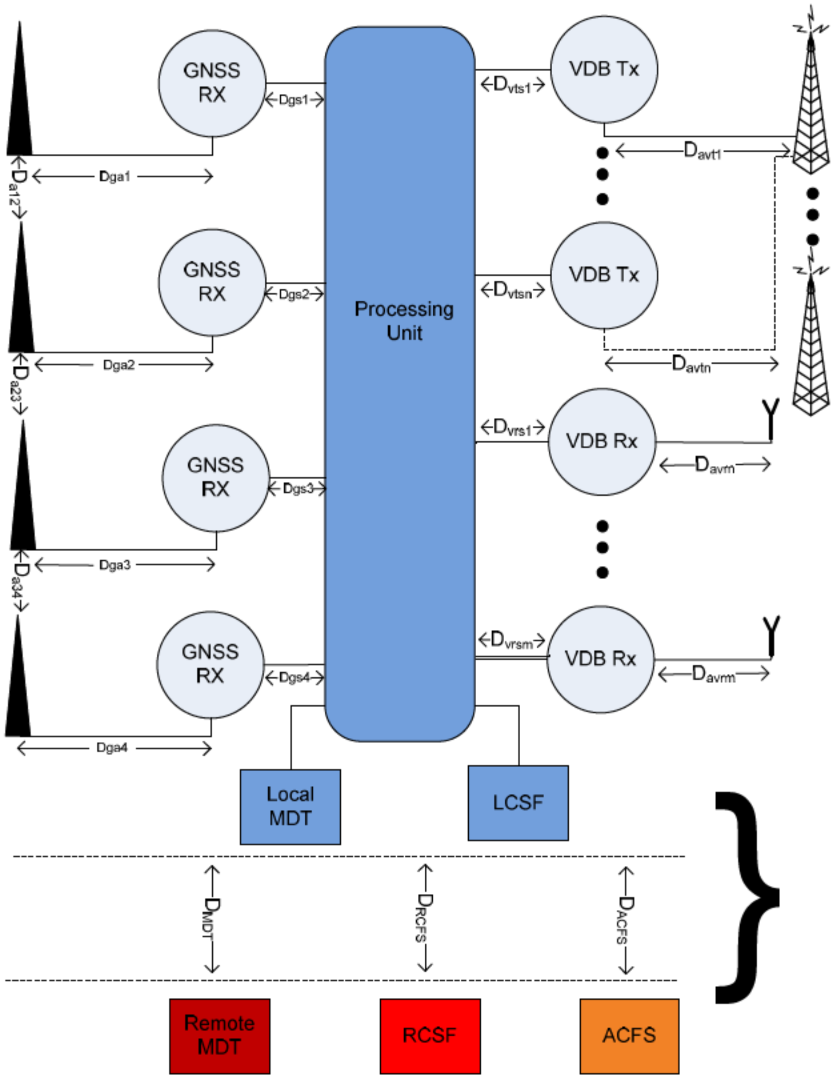


Figure 4-1: Manufacturer specific separation distances

Interface	Explanation	Separation requirement (manufacturer specific)
D_{ga1}	Antenna – GNSS RX 1	Normally a maximum, but a minimum could also be specified. Determined by type of cable, amplification in antenna and sensitivity of receiver
D_{ga2}	Antenna – GNSS RX 2	As above
D_{ga3}	Antenna – GNSS RX 3	As above
D_{ga4}	Antenna – GNSS RX 4	As above
D_{a12}	Antenna 1 – antenna 2	Normally a minimum and a maximum range, dependent on multipath rejection, ionospheric decorrelation and specific monitors.
D_{a23}	Antenna 2 – antenna 3	As above

D_{a34}	Antenna 3 – antenna 4	As above
D_{a41}	Antenna 4 – antenna 1	As above
D_{gs1}	GNSS RX 1 - shelter	For some architectures, the GNSS receiver may be located with the antenna. In this case, a maximum distance must be specified, dependent on the communication channel used.
D_{gs2}	GNSS RX 2 - shelter	As above
D_{gs3}	GNSS RX 3 - shelter	As above
D_{gs4}	GNSS RX 4 - shelter	As above
D_{vts1}	VDB TX 1 - shelter	Normally this distance is 0 (the transmitter is located in the shelter), but for some architectures, the VDB TX may be located separately, and a maximum distance is specified dependent on the communication channel used.
D_{vtsn}	VDB TX n - shelter	As above
D_{vrs1}	VDB RX 1 - shelter	This distance will normally be the same as $D_{vts1.}$ (VDB RX 1 is collocated with VDB TX 1), but other solutions may be foreseeable.
D_{vrsm}	VDB RX m - shelter	As above.
D_{avt1}	Antenna – VDB TX 1	Determined by the power output from the transmitter, the required minimum and maximum field strength, the antenna gain and the quality of the cable.
D_{avtn}	Antenna – VDB TX n	As above.
D_{avr1}	Antenna – VDB RX 1	This depends on the monitoring solution and will normally either be 0 (splitting of power on the output of the transmitter) or the same as the transmitter cable (Pickup antenna collocated with the transmitting antenna), but other solutions may be foreseeable.
D_{avrm}	Antenna – VDB RX m	As above
D_{MDT}	MDT – shelter	Depends on the communication channel
D_{RCSF}	RCFS – shelter	Depends on the communication channel
D_{ACSF}	ACSF - shelter	Depends on the communication channel

Table 2: Architecture Specific Siting Restrictions

In addition, LOCA must be determined around antennas. These are determined based on the antennas' sensitivity to reflections, i.e. the radiation pattern. Due to higher accuracy requirements, the LOCA may extend for CAT III compared to CAT I. LOCA assignments depend on receiver and antenna technology, so we do not expect an improvement in multipath when extending LOCA beyond those dictated by the technology. Therefore, we do not expect extended LOCA for GAST D, since the LOCA determined is based on the same technology we use in our GAST D prototypes.

When starting the siting process, it is recommended to identify potential sites for the GNSS antennas and the VDB antenna(s) independently, based on the general siting criteria. If a specific ground brand has been selected, also manufacturer-specific siting criteria must be taken into account. When possible areas for the GNSS and VDB sites have been identified, a combination of these should be selected based on:

- Security Aspects (S1)
- Obstacle limitation surfaces (S2)
- Distance between the two areas. Some architectures may allow the GNSS antennas and the VDB antennas to be sited relatively independently. However, in order to minimise cabling, the distance between the two elements should be minimised
- Climate conditions and seasonal variations (S8)
- Modification plans (S9)
- Reuse of existing infrastructure (S10)

4.2 Siting and Installation of GNSS Antennas and Receivers

The GNSS receivers can be mounted close to the GNSS antennas, and will then usually contain the power supply and lightening protection circuits [12]. Alternatively, the GNSS receivers are located within shelter, when the distances between antennas permit coaxial cabling.

As introduced in section 4.1 above, the following aspects for the GNSS antenna location should be considered:

- Security Aspects (S1)
- Obstacle limitation surfaces (S2)
- Maximum distance of 5 km from GBAS Reference Point to any threshold served by the station (S4)
- Horizontal/elevation mask (S5)
- Reflecting surfaces and multipath in the vicinity of the GNSS antenna (S6)
- Minimum separation and specific geometric arrangement between GNSS RRAs: related to the ionosphere gradient monitoring performance (S7)
- Any potential airport expansion/modification plans (S9)
- Distance to public areas: related to RFI aspects (S11)

All the above aspects are general and more or less independent of ground station architecture. LOCA/multipath aspects may differ slightly from ground station to ground station, but the differences will be small. Further details on multipath assessment can be found in sections 4.2.3, 4.2.3.1, and 4.2.3.2.

4.2.1 Maximum Distance between GRP and LTP (S4)

The primary siting criterion for the GNSS antennas is that the GBAS Reference Point (GRP) shall be located no further than 5 km from the Landing Threshold Point (LTP) of a CAT III runway being served.

This criterion has been introduced in the Development Baseline SARPs Proposal [8] §3.6.7.1.4 (siting criteria) for GAST-D.

4.2.2 Horizontal/elevation mask for GNSS RRA (S5)

Ideally, GNSS RRA sites should be chosen such that the base of the antenna has a clear horizon above 3° elevation at all azimuths. This will allow to acquire, verify and smooth the signal of a rising satellite for inclusion in the correction broadcast starting at 5° elevation. At these low elevations, even modest amounts of vegetation may block GNSS ranging signals. The horizon mask for an individual antenna site will determine the required antenna height, and should consider vegetation growth and the impact of nearby vehicles (for example, aircraft on a taxiway, and fire-fighting, maintenance, security vehicles). If the required height is excessive, another location should be considered. If no other options exist, the ideal antenna height has to be determined by trading off acceptable multipath performance and horizon masking. Where an antenna is to be located on the ground, it should be placed as low as possible. However, this increases the possibility of being covered by snow or being interfered with by maintenance personnel. An optimal phase centre height between 2 m and 3 m is recommended allowing for inspection from below and other airfield maintenance activities without impacting system availability. Greater antenna heights may be possible with reference antennas supporting GAD C. However, according to initial analysis GAD C type antennas are necessary in order to provide GAST D. As these antennas typically are relatively tall, suspended mounting is recommended in general in order to avoid phase centre variations.

Practically, it will in many cases not be feasible to avoid any masking. Even in areas where the terrain is benign, there may be buildings and constructions which mask out parts of the horizon. Early simulations results on the impact of the masking angle on the availability of GAST D are available in [16]. Normally, the shadowing which can be expected on an airport is assumed to result in acceptable availability reductions, however, the availability must be simulated during site qualification to ensure the suggested site has adequate availability performance. In general, the loss of GPS satellites below 5 degrees elevation will have minimal impact on system availability. If obstructions are identified that may block GNSS signals above this mask angle, then an analysis of the obscuration impact to system availability should be performed. This may also require that the ground system implements a variable horizon mask specifying different elevation cut off angles for specific azimuth ranges. The analysis should be confirmed by test measurements made during the site qualification if such sites are selected.

4.2.3 Multipath considerations for GNSS RRA siting and LOCA (S6)

Providing a site that is as free from objects having the potential to cause the combined reception of direct and reflected signals by the reference receivers (multipath) as possible is a key driver of GBAS ground facility performance. High levels of multipath may also mask the presence of other signal distortions. In general, GBAS reference antennas cannot tolerate any distinct multipath effects. It is important that service providers understand multipath phenomena, as monitoring multipath performance will be part of protecting the GBAS site during its entire service life. Within this section key multipath considerations with regard to GNSS antenna siting will be given. More detailed information on multipath phenomena and their determination follow in section 5.3

4.2.3.1 Multipath considerations for single GNSS RRA siting

Multipath sensitive areas should be established early. However, due to the complex nature of multipath it may be difficult to strictly define a protection zone with a simple, fixed radius. The LOCA (Local Object Consideration Area) is to a large extent defined by the antenna's susceptibility to multipath and the receiver characteristics. The definition of the LOCA is elaborated in the FAA document Siting Criteria for Ground Based Augmentation System (GBAS) [7]. The document defines criteria for a fixed combination of GNSS antennas and reference receiver, namely a multipath limiting dipole array type antenna with 0.1 chip narrow correlator E-L receiver. For other equipment, other definitions of the LOCA will result.

The LOCA for the combination of multipath limiting antenna with 0.1 chip E-L narrow correlator receiver consists of:

- an interior LOCA with a radius of 4 m in order to ensure the electromagnetic properties of the antenna incl. high elevation angle ground reflection incidence point control,
- an intermediate LOCA with a radius of 50 m following the extension of the antennas radiating nearfield and ensuring control of low elevation angle ground reflection incidence point, and
- an outer LOCA with a radius of 155 m following the correlators half correlator range.

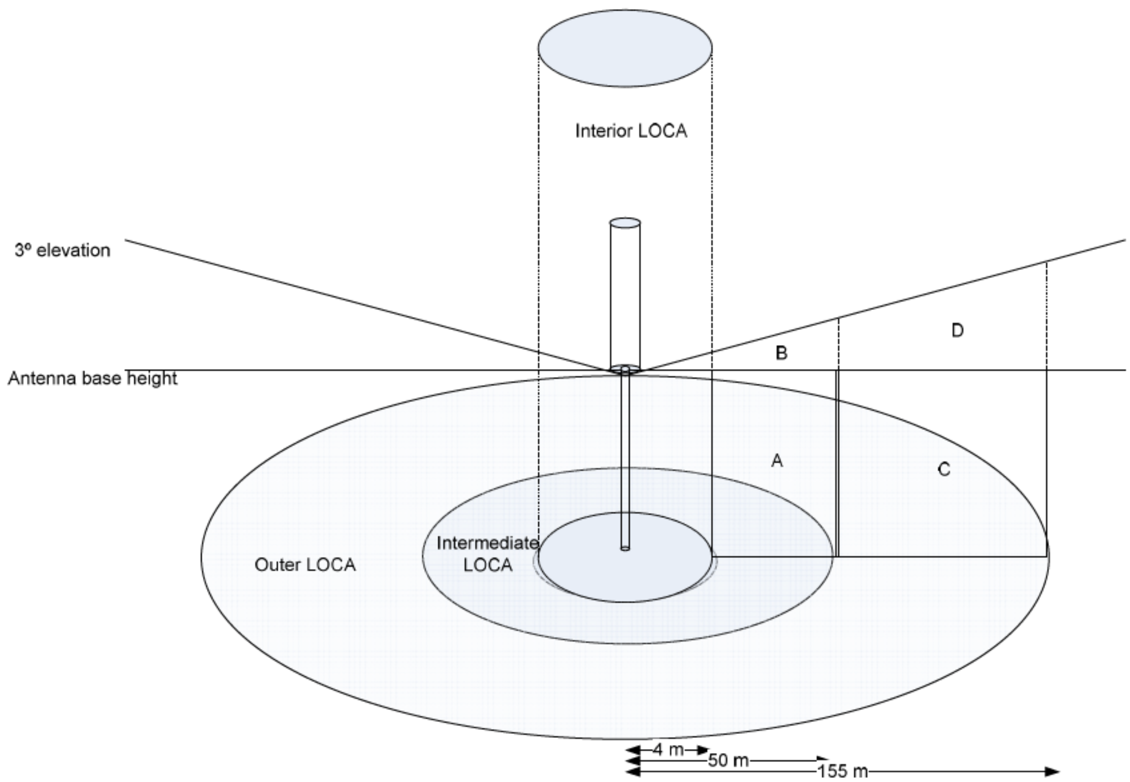


Figure 4-2 LOCA for the combination of multipath limiting antenna and 0.1 chip E-L narrow correlator

It recommends that no fixed structures are present within the LOCA. The possible impact of open shelter doors or hangar gates should be considered. Furthermore, any moving objects such as trucks or aircraft should also respect the 3° horizon mask. For large aircraft, it is considered sufficient to respect a 3° elevation angle from the base of the antenna to the top of the fuselage for most scenarios, which is generally not higher than 10 meters above a taxiway or runway. If a nearby taxiway includes holding points, the impact of tail fins should be evaluated. Some regions of the LOCA (typically > 50 m) may accept infrequent transients: irregular maintenance activities may typically be allowed.

Therefore, the impact of structures inside the LOCA has to be taken into account and compensated for in the transmitted σ_{pr_gnd}. This is normally accomplished during siting by logging data using the same type of antenna and receiver as the GBAS ground station.

4.2.3.2 Correlated multipath considerations for GNSS RRAs separation

Also, it is important to avoid multipath which is correlated between the GNSS reference receiver antennas. Correlated multipath affects the B-value calculations and pseudo-range corrections. Of particular concern are long buildings or lines of vegetation, in which case the antennas need to be staggered and/or varied in height. Any structures within the LOCA must be considered for potential correlated multipath. Correlated multipath from objects can result when two antennas can be influenced by the same object in a similar way.

Based on knowledge of the used antenna & receiver technology, criteria for a minimum separation between two antennas can be derived such, that correlated multipath is minimized. GPS receivers utilizing E-L correlators show a reduced susceptibility for multipath with a multipath delay longer than the C/A code chip spacing plus half correlator chip spacing. The envelope of the resulting multipath error is several orders of magnitude smaller for larger multipath delays (see also 5.3.2 for the multipath sources and the multipath error (envelope)). For narrow correlator E-L receivers with 0.1 correlator chip spacing this translates to a delay of 310 m. The shortest reflector distance leading to this multipath delay is 155 m. This follows from geometrical considerations for a multipath delay of 310 m. With regard to correlated multipath it can be concluded that two antennas need to be more than separated by the minimum reflector distance of 155 m in order to minimize correlated multipath. This separation distance reduces further, when certain assumptions on the LOCA will additionally apply. The LOCA is defined such, that no object – neither fixed, nor transient – is allowed to come closer than 50 m to a single antenna that is currently in operation. Now assume a (transient) reflector and two antennas, called antenna one and antenna two. From the LOCA definition the reflector cannot come closer than 50 m to antenna one and thus has the potential to cause multipath on antenna one as it is significantly closer than the above stated minimum reflector distance of 155 m. If it is the goal to minimize the potential to cause correlated multipath between both antennas from the same reflector, the two antennas need to be at least 105 m away from each other. Then it is ensured that the distance from the reflector to antenna two is at least 155 m.

With the above stated, the correlated multipath can only result for multipath delays outside the nominal multipath envelope, meaning for multipath delays longer than 310 m. The maximum error resulting outside the multipath envelope is dependent on the PRN's autocorrelation function properties, the receivers' pre-correlation filter properties and the reflectivity of potential objects outside the nominal multipath envelope.

With E-L receivers with 0.1 chip spacing of the correlators tracking pair, carrier phase multipath is also bounded by the multipath envelope, meaning the maximum multipath error on the carrier phase measurements for multipath delays longer than 310 m is significantly smaller than for shorter multipath delays. The remaining part outside the envelope again depends on the aforementioned influences.

From the aforementioned, it can be concluded that the resulting code carrier smoothed pseudorange error at the ground subsystem due to correlated multipath errors is small, but non-zero. These remaining errors from correlated multipath have to be considered in sigma_pr_gnd derivation.

Larger separation distances and their associated clear zones will occupy large areas of an airport. However, if not enough suitable candidate reference antenna locations can be identified in a single area, reference antennas may be placed throughout the entire airport area, resulting in separation distances much greater than 100m (remote reference receiver). If this is the case, special attention should be paid to protecting cable runs.

When correlated multipath from objects is minimized through siting, the ground reflection will remain as a source for correlated multipath (as long as the reference antennas are mounted with some distance above a flat ground surface). Minimizing the ground reflections multipath influence is primarily achieved with the used reference antenna/receiver technology. Additionally antenna height staggering helps to minimize the correlation of multipath resulting from the ground reflection.

4.2.4 Signal blockage considerations for single GNSS RRA siting

Generally, flying aircraft move too fast to have a multipath effect, but if flying directly overhead the antenna at a low altitude, some satellite signals may be blocked for seconds and reference receivers lose lock. Consequently, it is recommended to consider potential signal blockage from aircraft overflying the GNSS antennas.

In mid Europe (northern hemisphere), it could be a good idea to place reference receivers south of an approach path to minimise signal blockage. To the north, a reference receiver will typically see less satellites. Due to the inclination angle of the GPS satellites there are even no satellites at certain elevation angles in the northern direction. A polar plot of satellites tracks can help to identify these areas for a certain location.

4.2.5 GNSS RRAs separation and geometric arrangement (S7)

Apart the minimum separation distance between the GNSS Reference Receiver needed to avoid correlated multipath (see above), a specific geometric arrangement between the GNSS RRAs may be require to meet the ionospheric gradient monitoring performance requirement in GAST-D (Development Baseline SARPs Proposal [8] §3.6.7.3.4)

Nominally, without any constraint related to the ionosphere gradient monitoring, antennas could be arranged in a rectangular or triangular layout, but even a straight line up may be acceptable in a benign multipath environment.

Two ionospheric gradient monitoring schemes are being discussed for GAST D: the Absolute Slant Ionospheric Gradient Monitor and the Ionospheric Field Monitor (IFM).

The Absolute Slant Ionospheric Gradient Monitor requires a specific set of distances between the GPS receiver antennas. A first analysis presented in [26] shows that antenna pair baseline lengths of 200 to 400 meters are expected to meet the proposed ionospheric gradient monitoring performance in the draft GAST D amendments. A second analysis [32] shows that a configuration with 4 receivers and antenna pair baseline lengths of 62.03m, 116.8m and 219.9m can detect ionospheric gradients in a range of 300 to 2000mm/km with a probability of missed detection of 10^{-4}. The antenna separation is determined by noise figures, and the geometry needs to be adapted to runway geometry. Studies are ongoing with respect to this, and a preliminary assessment can be found in [49]. It should be noted that in case of loss of one reference receiver antenna, gradients relative to a specific runway direction may no longer be observable. More information on the impact of geometry on the observability of ionospheric gradients can be found in section 5.7.

The FAA Siting order [7] also imposes that no 3 RRAs should not be exactly collinear. This means that on a macroscopic scale, it looks that they are placed more or less in a line but on a microscopic scale, the lateral deviation is in the order of a wavelength.

However from the ANSP point of view expressed in the Siting discussion paper [5], it is necessary to limit the footprint of RRAs on the airport as much as possible. Therefore, the reference antenna separation distance in the case of this Absolute Slant Ionospheric Gradient Monitor should be the minimum one which allows to comply with the ionospheric requirement, i.e. 200 m.

The Ionospheric Field Monitor (IFM) is intended to be located at a different site than the ground station itself. For practical reasons it needs to be located inside the airport security fence. This is both for security reasons and because of the difficulties and airport will have in acquiring and maintaining properties outside the airport. There could be more than one monitor, e.g. one near each of the two most remote thresholds. This is assumed to be a more stable and reliable monitoring scheme, with far less strict requirements to the performance of the equipment with respect to noise. However, the monitors need to communicate back to the ground station the measurements performed, for the measurements to be synchronised with measurements performed there. Therefore, some infrastructure needs to be in place for this purpose, which is the most important argument against this monitor. However it can be argued that all CAT III ILS's in the world uses far field monitors on all CAT III thresholds (see 3.3.4), so this type of infrastructure must be established also for other CAT III landing systems.

It has to be noted that the feasibility of IFM monitoring is also subject to current research. This incorporates the gradient detection need in dependence of separation, and separation in dependence on noise. Assuming that it is based on code measurements in order to avoid the carrier phase double difference ambiguity problems, the noise drives the needed baseline length. Preliminary results indicate that it may not be able to cover the whole detection range alone, since the necessary baselines lengths are rather high. Further evaluations are needed to get a clear picture on possible advantages of IFM architectures.

4.2.6 Distance to public areas: related to RFI aspects (S11)

RFI (Radio Frequency Interference) considerations may impact the GNSS RRAs siting. Generally, public areas such as highways, parking lots etc. are particularly likely sources of RFI as PPDs (Personal Privacy Devices) in the form of GPS jammers are occasionally used on cars/trucks. The range of these devices is normally limited. GPS repeaters installations at an airport are also a possible source of RFI.

Due to the normally limited range of jammers and repeaters, the risk of loss of continuity and availability due to interference can be reduced by moving the GNSS part of the ground station as far away from public areas (public roads, airport terminals etc) as possible. The robustness of the ground station is mainly influenced by reference antenna characteristics, reference receiver design, and may vary from architecture to architecture. I.e. some architectures may be able to operate with one or more GNSS receivers out of operation due to jamming for some period of time, and it may also vary whether a station can recover from a loss of signal due to jamming. Due to this, it may help even if only some of the receivers can be located away from public areas, whereas others are located relatively close. A paper produced within 15.3.6 as part of the GAST D validation, in order to follow up on the issues identified in D03, addresses the performance of the monitors based on the ground station GAD performance. It also looks at the monitor performance as a function of number of operational receivers, refer to [18] for more details. Based on a general monitor, it is shown that the ground station may be able to operate in GAST D with three operational receivers for a limited period of time if the antenna configuration is suitable for this. This indicates that it is possible to design a ground station which can be relatively robust against short-term, limited range RFI (such as jammers in cars) based on four receivers. Reference antennas can be installed quite low. Installing a fine mesh (~1 cm) metal fence between the GNSS RRA and the public area could attenuate interference signals. Originally, increasing the antenna height was expected to reduce the problem due to the antenna gain pattern for low elevations. But trials of the FAA at Newark showed increasing problems for higher antenna elevations, due to increasing field strength from the PPD.

4.3 Siting and installation of VDB Tx and Rx antennas

The VDB transmitter and VDB receiver are also part of the GBAS GS, and as the GNSS antennas, they are usually connected to the cabinet by cables. Architectures where the VDB transmitter is co-located with the transmitter antenna are also possible. In this case, the VDB receiver will typically be co-located with the VDB transmitter. In architectures with more than one transmitter/receiver pair, one pair could be located in the shelter, whereas others may be co-located with the remote transmitter antenna.

As introduced in section 4.1 above, the following aspects for the VDB antenna locations should be considered:

- Security Aspects (S1)
- Obstacle limitation surfaces (S2)
- Coverage volume (S3)
- Any potential airport expansion/modification plans (S9)

4.3.1 Considerations related to obstacle limitation surfaces (S2)

As described in Appendix A in this document, ICAO Annex 14 defines a number of obstacle limitation surfaces, which are intended to restrict the siting of objects in areas on and around the runway region. In general, the siting of the VDB antenna should comply with the necessary obstacle restriction criteria defined in ICAO Annex 14. As restrictions vary according to the particular characteristics of the runway(s) in question with the possible use of clearways, runway end safety areas etc. an assessment of the limitations will need to be carried out for the individual aerodrome in question. The Obstacle Free Zone and other Clear and Graded Areas must be respected when planning a site. Exceptions from Annex 10 rules may be necessary for dense airports and may be sought when feasible. A possible exception is defined in Annex 14 for equipment and installation required for air navigation purposes which must be located on or near a strip of a precision approach runway category I, II, III (Annex 14 Vol. I, 9.9.6). This exception is currently used for ILS and MLS installations only, which require antenna and equipment installations in these areas to provide the required function. GBAS is not required to be placed close to runways to provide its function and GBAS is not mentioned in the ICAO documents to make use of this exception.

The following figures use simple examples to give the reader an idea of necessary separation of obstacles like antennas from operational areas. Figure 4-3 provides an idea about possible obstacle heights as a function of distance from the runway centre line (zoom in of Figure 9-2 in Appendix A for a CAT II/III precision approach runway).

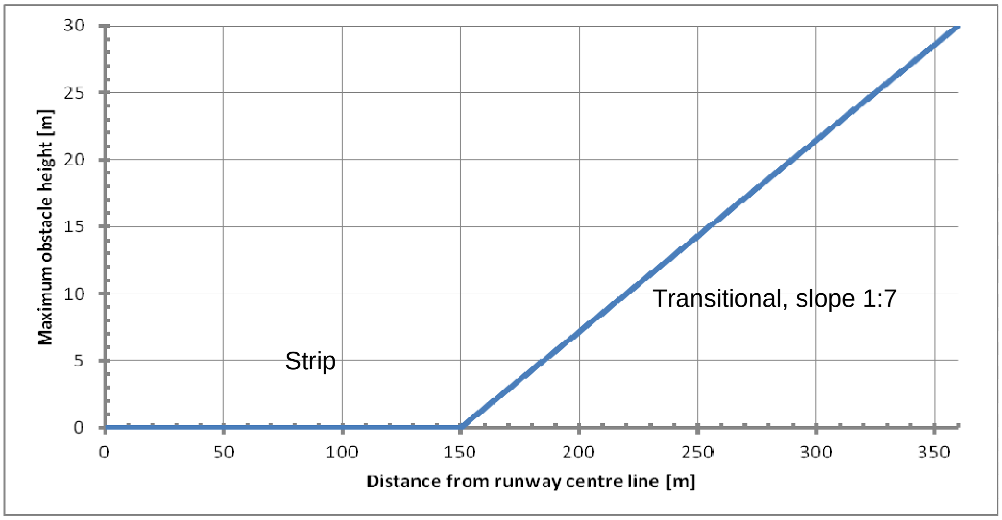


Figure 4-3: Maximum obstacle height as a function of distance from runway centre line for a CAT II/III runway

Underneath the approach path the maximum obstacle height is depicted in Figure 4-4.

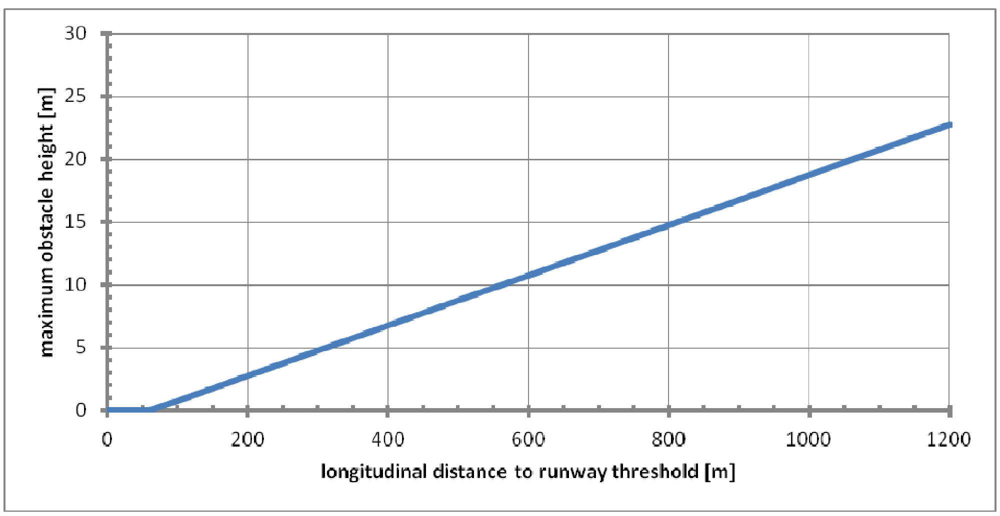


Figure 4-4: Maximum obstacle height underneath the approach path as a function of distance from runway threshold for a CAT II/III runway

For taxiways the strip on each side of the centre line is smaller than for runways. The maximum is 57.5 m for a Code F taxiway. More detailed requirements can be found in ICAO Annex 14 Vol. I chapter 3.11.2 and table 3-1 column 11 of the ICAO Annex for taxiways Code A to E.

In addition to these requirements, it may be necessary to observe other restrictions on the aerodrome and in the vicinity of the aerodrome in order to protect the performance of visual and electronic aids to navigation and to ensure that instrument approach procedures and the associated obstacle clearance limits are not adversely affected. The chosen location should observe any siting restrictions through critical and safeguarding areas of existing or planned ATS systems (ILS, VOR, etc).

As an output of this task, we would suggest to identify issues that would be candidates for a review of Annex 14 in order to provide more flexibility for installation of GBAS, taking the above-mentioned considerations into account.

4.3.2 Criteria related to VDB coverage volume (S3)

The VDB coverage area is defined as follows in the GAST D Development Baseline SARPs Proposal [8]:

o Minimum GBAS coverage for approach services in [8] § 3.7.3.5.3.1:

"The minimum GBAS coverage for approach services shall be as follows, except where topographical features dictate and operational requirements permit:

a) laterally, beginning at 140 m (450 ft) each side of the landing threshold point/fictitious threshold point (LTP/FTP) and projecting out ±35 degrees either side of the final approach path to 28 km (15 NM) and ±10 degrees either side of the final approach path to 37 km (20 NM); and

b) vertically, within the lateral region, up to the greater of 7 degrees or 1.75 promulgated glide path angle (GPA) above the horizontal with an origin at the glide path interception point (GPIP) to an upper bound of 3 000 m (10 000 ft) height above threshold (HAT) and 0.45 GPA above the horizontal or to such lower angle, down to 0.30 GPA, as required, to safeguard the promulgated glide path intercept procedure. The lower bound is half the lowest decision height supported or 3,7 m (12 ft), whichever is larger"

o An additional requirement is in place in [8] § 3.7.3.5.3.2 to support autoland:

"3.7.3.5.3.2 Approach Services Supporting Autoland. The minimum additional GBAS coverage to support approach operations that include automatic landing and rollout shall be as follows, except where operational requirements permit:

a) Horizontally within a sector spanning the width of the runway beginning at the stop end of the runway and extending parallel with the runway centre line towards the LTP to join the minimum operational coverage region as described in 3.7.3.5.3.1

b) Vertically, between two horizontal surfaces one at 3.7 m (12 ft) and the other at 30 m (100 ft) above the runway centreline to join the minimum operational coverage region as described in 3.7.3.5.3.1. "

o An additional recommendation in [8] § 3.7.3.5.3.3 is in place to cover special aircraft types and antenna configuration:

"3.7.3.5.3.3 ***Recommendation*** *– Vertical coverage in sections 3.7.3.5.3.1, 3.7.3.5.3.2 should extend to 2.4 m (8 ft) above the runway surface."*

The first criterion, "coverage of all operational areas" implies that the minimum field strength in all operational areas shall be 215 microvolt per metre (–99 dBW/m^2). Therefore, the VDB transmit antenna location should be such that the radiated signal is as unobstructed as possible, ideally an unobstructed line-of-sight should exist from the antenna to all operational areas, including runways for roll-out. Minor fixed structures may be allowed in the line of sight. Diffraction around corners and propagation through light buildings like wooden shelters may cause there to be coverage also behind structures which obstruct the line of sight. Tools to simulate such phenomena are available for purchase at different price levels depending on complexity. Relatively reliable simulations can be performed for simple scenarios, however, as the scenarios are more complex, simulations will be less accurate. Unless such simulations are performed or preliminary measurements are made, it must be assumed that line-of-sight is required except for light buildings and relatively small structures. Also, taxiways between the transmitter and the operational areas may be a challenge and should be minimised. Coverage of all runways on an airport from a single transmitter is considered to be a difficult siting requirement. For complex airports, it will be difficult or impossible to find a single site which has line-of-sight to the entire length of all CAT III runways (threshold to threshold).
The antenna should generally be located as high as practical. Increased antenna height may be needed to provide adequate signal strength to users at low altitudes, but may also result in unacceptable fading losses within the desired coverage volume. Siting the transmitter antenna at the top of a building is one alternative to assess: However, due to the characteristics of horizontally polarised signals, this solution has some disadvantages. The height of the building will add to the antenna height, and the higher the antenna is over ground, the more lobbing will occur. Any fading losses greater than 10dB could result in insufficient coverage. Reflections from objects in the

surroundings of the antenna will tend to fill the fade holes in the antenna pattern, but this needs to be simulated in each particular case to ensure that there will be no fade holes that will violate the coverage requirements. Depending on antenna height and type, an area with a radius of 500 to 1000 m may be relevant (first reflection zone / image). Fade holes and coverage holes due to shadowing may alternatively be filled with additional transmitters transmitting in separate time slots. VDB antennas could be installed at different locations or at the same location at different heights.

The minimum field strength requirement imposes a maximum distance restriction as well. Allowing for adequate margins for fading, operating margin and implementation loss , the maximum distance from the most distant point in the coverage area (20 NM from threshold) to the VDB antenna, should be 23 NM (see e.g. [1]). This implies that the VDB antenna should be located within a radius of 3NM (approximately 5,5 km) from any threshold being served. This applies to CAT I, II or III runways.

Although the same requirements with respect to coverage of the runway apply for CAT III localizers, an additional challenge is imposed on GBAS since the target is to cover an entire airport with several runways by a single ground station. However, since it is the GPS part which is the major cost driver for a station at the time of writing, it could be considered to install more than one VDB transmitter/antenna for a single ground station.

4.3.3 Criteria related to the maximum VDB field strength (S3)

Two requirements dictate some minimum distances from the VDB transmitter antennas:

- Maximum field strength requirement: imposes minimum distances to operational areas where GBAS services are used, i.e. approach path and runways.
- Airborne receiver burnout requirement: Imposes minimum distances to taxiways, apron, hangars and other areas where GBAS equipped aircraft may be operated without using GBAS services.

The maximum VDB signal strength requirement as given in the ICAO Annex 10 Baseline Development Standard [8] is 0.350 volts per metre (–35 dBW/m^2). This value is consistent with a minimum distance of 200m from the transmitter antenna to operational areas. This minimum distance can ensure that user receivers do not saturate. However, recent work within RTCA takes into account a higher minimum aircraft implementation loss, allowing a higher maximum field strength of 879V/m. Allowing for constructive fading and relatively high aircraft antenna gains, the minimum distance to operational areas (runway and approach) is in the order of 80 m. The RTCA work related to this requirement change is summarised in [29]. However, locating the VDB antenna closer to runways than this will normally not be possible anyway, due to ICAO Annex 14 restrictions. These are summarised in [13].

The airborne receiver burnout requirement is 20dBm [31], which requires a minimum distance of approximately 7 m to taxiways etc, refer to [29].

4.3.4 VDB antenna LOCA (S3)

The VDB antenna LOCAs are defined volumes around the VDB antenna(s) within which stationary objects have a high potential to cause unacceptable degradation of system performance. Objects located within the VDB Antenna LOCA may either block the VDB signal or generate reflections that cause nulls in the VDB signal in operationally significant regions of its coverage volume. The manufacturer shall provide the dimensions of the VDB Antenna LOCA.

4.4 Siting and installation of Shelter/Ground Subsystem

Siting of the shelter should be considered after possible locations for the GNSS receiver part and the VDB part has been identified. The aspects to consider are:

- Security Aspects (S1)
- Obstacle limitation surfaces (S2)
- Climate conditions and seasonal variations (S8)
- Modification plans (S9)

- Reuse of existing infrastructure, e.g power and communication lines (S10)
- Location of the shelter relative to Reference Receiver and VDB antenna to avoid unacceptable multipath or signal blockage caused by the shelter. The shelter should be located outside the Local Object Consideration Area (LOCA) (Partly covering S5 and S6)
- Distance between the two areas (VDB site and GNSS site) to minimize cabling. This has major importance with the VDB antenna because power of transmitted signal is a keypoint to meet coverage.
- Ease of access (site access roads).

Besides the location requirements, other considerations are:

- Adequate protection from high-voltage circuits for supplying radio transmitters
- Needed space for housing the processing equipment and sufficient space around it for service personnel to work, see section 6.4.2.4
- Environmental considerations, see section 6.4.2.4

The siting requirements for the shelter itself are not very restrictive. But it is an advantage to house as much as possible of the equipment (GNSS receivers, VDB transmitters and receivers) inside the shelter, in order to avoid having to install separate housings for these items.

The shelter must provide climate control in order to keep the environment within the limits specified for the ground station in question. Guidelines as to which environmental specifications can be expected can be found in ED-114 [1]. The performance of the equipment is guaranteed within the environmental limits specified for the equipment in question. However if the temperature can be stabilised between 10 and 25°C, this increases the reliability and lifetime of electronic equipment in general.

The shelter will also contain batteries/UPS, grounding, lightening and over-voltage protection on cables going in and out. The shelter should not house equipment that produces conductive gases, except equipment with small amounts these gases, such as lightning protection equipment, fluorescent lights etc.

The shelter provides a physical security barrier for the equipment it contains. Refer to section 5.6 for a discussion on security threats and measures. The shelter should be locked when no authorised personnel are present, and it could be considered to install an intrusion alarm.

4.5 Equipment Control and Status

The Ground Subsystem will provide detailed information to support Maintenance and ATC requirements (see reference [23]). This information will be based on status and control functions on local and remote position. Functionality is further detailed in 15.3.6 D020 [27] (GBAS GAST D ConOps), whereas its location is the main scope of this section.

The following subsystems are considered:

- Local Control and Status Subsystem:
  a) Local Control and Status Unit (LCSU) at §4.5.1
  b) Local Maintenance Data Terminal (LMDT) at §4.5.2.

- Remote Control and Status Subsystem:
  a) Remote Control and Status Unit (RCSU) at §4.5.3.
  b) Remote Maintenance Data Terminal (RMDT) at §4.5.4.
  c) ATC Control and Status Unit (ATCU) at §4.5.5.

Appropriate technical control may be provided to make sure that the ground subsystem can only be controlled locally or remotely from one control subsystem at any time.

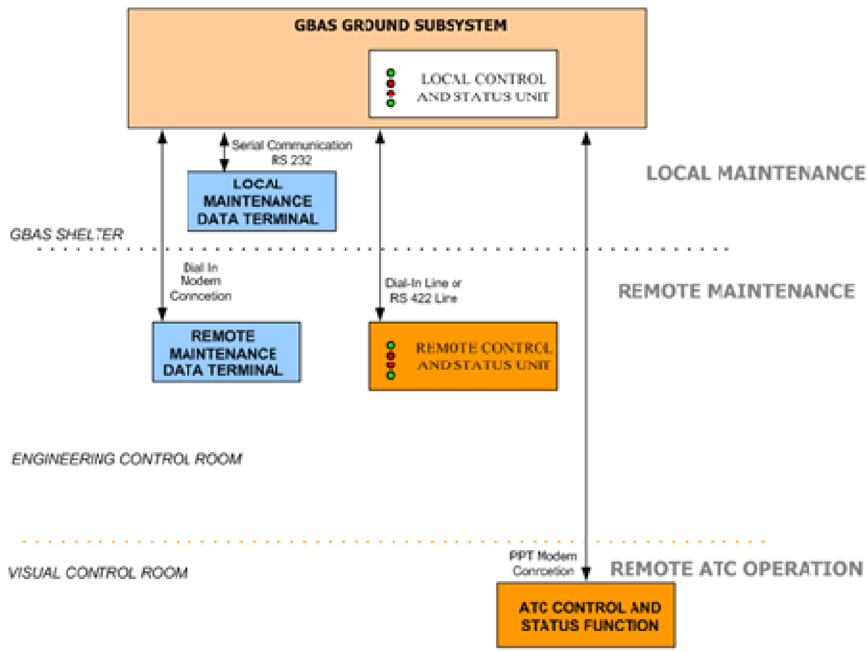


Figure 4-5: Overview of Local/Remote Control and Status (See reference [23])

4.5.1 Local Control and Status Unit (LCSU)

The Local Control and Status Unit (LCSU) provides full operational control and status functions at the location of the Ground Subsystem (GS). This shall provide the full local control of the GS as well as a display of the status of the equipment. A means to input site-specific GBAS related data shall be provided locally at the GS.

These functionalities should be available at the GS equipment itself in the GBAS shelter by means of interfaces that communicate directly with the GS.

4.5.1.1 Local Control Function

Means shall be provided for full local control of the equipment. These can be provided by hardware or by software. It shall include at least:

i) Enter and exit Maintenance/Test Mode or Mode Selection control for Local, Normal and Maintenance/Test Mode.
ii) ON/OFF control of the VDB transmission.
iii) Manual “Reset” to shutdown and automatically restart the Ground Subsystem equipment.
iv) Aural alarm reset for the LCSU (mute).
v) “Indicator test” for the LCSU.
vi) Power ON/OFF
vii) Switch between AC power and battery/auxiliary power (if provided).

4.5.1.2 Local Status Function

The operational status of the equipment and the Ground Subsystem failure status shall be provided. To achieve this, the minimum local indications to be implemented shall be the following:

i) a "Normal" indication which is displayed when the equipment is operational and no executive alarm has been generated.
The indication shall also include the GAST operational mode, i.e. GASTD or GASTC depending on the GASTD monitors and the VDB signal transmitted by the GS.

ii) an "Alarm" indication which is displayed when the equipment is not available through the generation of an executive alarm or other means. It is recommended that additional indications are provided to indicate the executive monitor function which initiated the alarm as well as the specific parameter which caused the alarm condition.

iii) a "Maintenance alert" indication to signify when a maintenance alert has been generated.

iv) a "Maintenance" or "Test" indication which is displayed when the equipment is in Maintenance Mode for maintenance purposes and therefore not operational.

v) a "Battery" or "Auxiliary Power" indicator shall be provided to signify the equipment is being powered by the auxiliary source.

vi) Indication of the status of major Ground Subsystem components (processors, transmitters, etc.) including the duplicated or redundant components. This indication may be provided through the Local Maintenance Data Terminal.

4.5.2 Local Maintenance Data Terminal (LMDT)

An interface shall be provided to enable connection between the GBAS Ground Subsystem equipment and a Local Maintenance Data Terminal (LMDT) to assist maintenance personnel during installation, commissioning and maintenance activities.

This interface shall be accessible from the GBAS shelter to connect directly with the GS equipment.

LMDT includes status displays, events and alerts/alarms recording and diagnostics performances, which are further described in 15.3.6 D020 [27] (GBAS GAST D ConOps).

4.5.3 Remote Control and Status Unit (RCSU)

The Remote Control and Status Unit (RCSU) is intended to provide basic operational control and status functions at remote positions. The RCSU should be install in the engineering control room and provides similar functionality to the LCSU. The implementation of this unit is optional.

4.5.3.1 Remote Control Function

The remote control function is optional. If the remote control function is implemented means shall be provided for control of the equipment via the RCSU as follows:

i) ON/OFF control of the VDB transmission.

ii) Manual "Reset" to shutdown and automatically restart the Ground Subsystem equipment.

iii) "Indicator test" for the RCSF.

iv) Aural alarm reset for the RCSF (mute).

Within the RCSU a means may be provided to disable (and subsequently enable) all or individual approaches associated with each runway end served by the equipment. This will have the action of setting the FASLAL fields of the relevant FAS data sets to all 1's (do not use approach).

Note: Current concept of operations for GBAS does not require disabling and enabling of approaches.

4.5.3.2 Remote Status Function

A change in operational status of the GBAS ground subsystem shall be displayed at the remote status display within 2 seconds (actually no common requirement is agreed on an international level, the value ranges between 1 to 5 seconds) excluding network lag times [1], [10] (requirement 3.6.1.3 for 1s).

The minimum remote indications to be implemented shall be the same as for the local control status function (see §4.5.1.2), plus:

vii) an indication shall be provided to reflect the status of each approach path defined in the system.

4.5.3.3 Remote Units location

Location of RCSF should be in the engineering room.

Criteria for siting remote units will be primarily in the human factors area and shall be coordinated with the end users of the equipment. Mounting requirements and proximity of power shall also be considered when siting the remote units.

The main constraint to locate the engineering room is the availability of communication lines to remotely connect the GS. The length of the communication lines is a cost limiting factor. Also it might be possible to use the existing communication lines (dependence on transfer protocol/ required transmission rate).

4.5.4 Remote Maintenance Data Terminal (RMDT)

The implementation of the Remote Maintenance Data Terminal (RMDT) is optional. The RMDT provides an interface for maintenance personnel. It is devised to assist maintenance personnel during basic planned/unplanned maintenance activities. Remote changes to integrity parameters shall not be permitted.

The RMDT is intended to be connected in an engineering control room, where an interface should be provided to enable connection between the GS equipment and the RMDT.

RMDT includes status display capabilities which are described in 15.3.6 D020 [27] (GBAS GAST D ConOps).

4.5.5 ATC Control and Status Unit (ATCU)

No international standards for ATC interface are available. The needs and the resulting ATC interface design is driven by the respective national regulations. Integration within the existing interface for approach and landing systems should be considered.

This might lead to designs, where the ATC interface not only provides GBAS related information, but also merged information acquired from different sensors is provided to the ATCO. Such sensors are providing information on the runway lighting status, weather information and GBAS ground station status information.

However, according to ED-114 [1], 15.3.6 D020 [27] and the 6.8.5-15.3.6 AU workshop summary [28] general needs and common requirements could be established to design the ATC interface.

4.5.5.1 ATCU location

The ATCU is intended for installation in the Visual Control Room (typically at several ATC positions).

However, GBAS Status and Control functions may also be provided at different control positions (approach or tower).

4.5.5.2 ATCU Control and Status functions

The ATCU basically includes status functions and control functions.

4.5.5.3 ATCU Status functions

As one GBAS ground system may provide approach and landing service for several runway ends versus one ILS system per runway end, it is important to discern between GBAS ground system status and GBAS approach service potentially available at a particular runway end.

According to the 15.3.6 D020 [27] and the 6.8.5-15.3.6 AU workshop summary [28], the ATCO is more concerned by the availability of the service (CATII, CATI…) per approach rather than the GBAS station status. ATCO should be informed of the aircraft equipment (i.e. GBAS and/or ILS capable). This is all the information needed by the ATCO to clear the GLS CAT II/III approach.

Therefore, the ATCU should at least display the GBAS approach service status as seen from the GS. The station status could be provided to the ATC supervisor.

4.5.5.4 ATCU Control functions

The implementation of ATC Control functions is optional. If Control functions are implemented, a means to disable (and subsequently enable) all or individual approaches associated with each runway end served by the equipment should be provided.

According to the 15.3.6 D020 [27] and the 6.8.5-15.3.6 AU workshop summary [28], some ANSPs prefer to keep it simpler so that the ATCO does not enable/disable GBAS approaches whilst other ANSPs allow the ATCO to enable/disable runways.

For ILS, an opposite runway end approach is disabled due to electromagnetic interference issue. As GBAS would have no such interference problem, both runway ends may remain enabled. Nevertheless ATC argued that enabling and disabling opposite runway ends is used also for other operational purposes, such as to avoid misunderstandings regarding the cleared runway end to land. If such solution is retained, the enabling/disabling approach is the mandate of the ATC supervisor. Therefore a safety assessment may need to analyse the scenarios for which the option should be retained.

In case GBAS ground station technical problems, it is not the role of the ATCO to disable the GBAS approaches but preferably to the maintenance staff.

4.6 Connections and External Interfaces

GBAS ground subsystem internal interfaces are highly manufacturer dependent. Therefore a generic representation is hardly achievable and may not provide added value. For this reason these internal connections are not considered here.

Instead all external interfaces needed for operation of the ground subsystem will be covered in a generic way.

These cover all Connections to the aforementioned external interfaces:

- LMDT
- ATCU
- RCSU
- RMDT

As well as data logging provisions provided by the ground subsystem.

The LMDT is typically connected to the ground subsystem directly. The connection type is manufacturer dependent. The connection is designed such that the intended functionality - to perform configuration and SW updates on the ground subsystem - is given. The airport infrastructure is not touched by this connection.

The RCSU, RMDT and ATCU connections are dependent on local airport infrastructure. The basic architecture may vary due to driving factors such as layout of communication infrastructure with dedicated lines, fiber optic network and supported communication protocols e.g. RS-232 or TCP/IP. The required implementation of the remote units and functions should permit flexibility in order to be adaptable to different ANSPs and airports requirements.

According to ground station MOPS for CAT I (draft ED-114 rev. A, [52]) the ground subsystem shall provide a capability to output data in real-time from a data logging communications port. The primary purpose of this communications port is to provide certification authorities with the necessary real-time data for qualification purposes. Additionally this data may also be used to satisfy legal data recording requirements.

From this port the below described time-tagged variables from the code, observable parameters and events are provided.

The primary purpose of this communication port is to provide certification authorities with the necessary real-time data for qualification tests. Additionally this data may also be used to satisfy legal data recording requirements, reliability recording (e.g. MTBO monitoring) and operational needs (e.g. tools).

Depending on the architecture designed by the manufacturer, the GBAS Ground Subsystem may consist of several individual units. Hence, this 'Data Logging Port' could be, in reality, composed of several individual ports originating from these different units.
The port should be a standard RS-232, RS-422 or RS-485 port, with the following characteristics:
-The maximum configurable rate should be not less than 115200 baud.

- 8 data bits
- 1 stop bit
- no parity
- DB9 connector, male.

The user can connect one or several PCs to this port in order to log the data with commercially available communications package or specifically developed software provided by the manufacturer. The manufacturer should provide a detailed specification of this port and the data provided (including parameter description, units, range, resolution and update rate for each measurement).

Each data set should be protected against data corruption by 32 bits CRC.

Alternatively, a network interface could be provided. In that case, a dedicated Ethernet port supporting standard protocols like ftp should be provided to download internally recorded data.

The Data Logging Port should support different types of information to be output:

- Messages or Events
- Observable Parameters and Variables
- Data Files (internally collected data that may be downloaded)

The information should be output at a minimum rate of 2Hz, in configurable ASCII or Binary modes, but the two modes could be mutually exclusive.

Each individual information should be time-tagged with both UTC Time and the GPS Time at which it was elaborated and declared valid.

a) Messages – Events

Messages or Events are information output that characterises the status and actions of the Reference Station subsystems, such as Monitoring Function or Reference Receivers.

b) Parameters - Variables

Parameters should represent the current value of internal variables and are output once for each GBAS Message that is generated for transmission.

All the parameters included in the broadcast messages (Type 1, 2, 4 and optionally Type 5 if used) should be available through the Data Logging Port.

In addition, the following list of internal parameters in an appropriate resolution should also be available:

a)Ground Subsystem Parameters:

#	Parameter Name	Description	Unit
1	GPS Time	Current GPS Time of week used to calculate the broadcast Z-count	s
2	GPS week number	GPS week number	-
3	Ground Station Status	Mode of operation , alarm and alert status	-
4	VDB Status	VDB status information including information of which transmitter is active	-
5	VDB Power Level	VDB Field measurement	dBm
6	B_1 to B_4	B-values with 0.05 m resolution[2]	m
All other parameters from the GBAS message Type 1, 2, 4 and if used Type 5 …			

b)Reference Receiver Parameters:-

For each installed Reference Receiver (2 up to 4), the following list of parameters should be available:

#	Parameter Name	Description	Unit
1	GPS Time	GPS Time of week for the receiver parameters measurement or calculation	s
2	GPS week number	GPS week number	-
3	Reference Receiver Status	Status of the Reference Receiver as described by the receiver manufacturer	-
4	Antenna position	Position in the WGS84 of the receiver antenna (Lat, Long, Alt)	° (degrees)
5	Visible SVs	Number of visible SVs above mask angle	-
6	Valid SVs	Number of valid raw measurements (code and carrier)	-
For each valid (tracked) satellite (i), the following information should be provided			
7	PRN (i)	PRN number of the range measurement i	-
8	Azimuth (i)	Azimuth angle from the antenna	° (degrees)
9	Elevation (i)	Elevation angle to the satellite from the antenna	° (degrees)
10	P (i)	Raw Pseudo-range Measurement	m
11	Φ (i)	Carrier-Phase (Accumulated Doppler Range) measurement	m
12	C/No (i)	Carrier to Noise density ratio	dBHz
13	Tracking Status (i)	Tracking status for PRN channel as described by the receiver manufacturer	-
14	P_{CSC} (i)	Carrier-smoothed code pseudo-range	m
15	PRC(i)	Pseudo-range Correction for the i^{th} SV and the j^{th} RR	m
16	RRC(i,j)	Range Rate Correction for the i^{th} SV	m/s
17	σ_{pr_gnd}(i)	Sigma Pseudo-range Ground for the i^{th} SV and the j^{th} RR	m
18	B_{PR}(i)	B-value for the i^{th} SV	m
…	…	…	…

NOTE: *This list is given as an example and should not be limited to the above parameters*

[2] The resolution of 5 cm is valid for broadcast B-values typically available when VDB broadcast data (as transmitted) will be logged. For test purposes, B-values with higher resolution are useful in order to shorten the measurement times. It has to be noted that the availability of such high-resolution data from internal processing might deviate between the ground equipment manufacturers.

c)Satellite Orbit Parameters:-

The ground subsystem should provide the verified ephemeris data (e.g. in a RINEX compatible navigation message with all optional header information) and the most recent signal in space almanac data (e.g. in a YUMA compatible message format).

5 Special challenges

The GBAS GS is installed in order to provide corrections to approaching aircrafts, i.e. corrections on errors correlated between the aircraft and the GS. There are however also uncorrelated errors, and these errors represent a special challenge, and have to be mitigated in order to preserve integrity, continuity and availability [12]. In addition, some errors de-correlate with distance to the ground station, such as pseudorange errors due to ionospheric and tropospheric refractions. These aspects impose some siting restrictions. One of the most restrictive siting requirements is the one imposed by the Baseline Development SARPs, [8], Appendix B, section 3.6.7.1.4.1:

“The distance between the reference point of a FAST D ground subsystem and the LTP of any runway for which the ground subsystem supports GAST D shall be less than or equal to 5 km.”

This requirement is in place in order to limit the pseudorange correction error caused by decorrelation of the ionospheric error. For a large airport, this requirement may be difficult to meet with only one ground station. This aspect is elaborated below. For dual-frequency GBAS systems which will be possible in the future, the impact of the ionosphere can be estimated and this siting restriction may therefore be removed or relieved. Siting may therefore become easier for dual-frequency GBAS. For GAST D however, some architectural means can be used to ease the siting of the GAST D ground station slightly. This is addressed below.

5.1 Challenges related to general siting restrictions

The general siting restrictions are listed in the following table.

ID	Siting Criteria	Applicable Architectural element
S1	Security aspects: The ground station and at least the GNSS receiver antennae must be installed in secure areas, inside the airport fence.	GNSS Shelter/Processing unit VDB
S2	Airport siting considerations, considerations related to obstacle limitation surfaces	GNSS Shelter/Processing unit VDB
S3	Coverage volume: o The minimum field strength requirement needs to be addressed. The radiated signal is as unobstructed as possible, ideally there should be line of sight to all operational areas. LOCA should be respected. o The VDB antenna is not located more than 3NM from every runway threshold o The maximum field strength requirement needs to be addressed, restricting how close to operational areas the VDB transmitter can be located. The airborne receiver burn-out requirement is also considered.	VDB
S4	Maximum distance from GBAS reference point to any threshold served by the station is 5km (GAST D specific) in order to mitigate ionospheric anomalies.	GNSS

S5	Horizon/elevation mask: obstacles above 3 degrees should be avoided for the GNSS antennas if possible, as shadowing may impact both availability and continuity. The siting area should be predominantly flat and with low/limited vegetation	GNSS
S6	Reflecting surfaces in the vicinity of the GNSS antennas: Multipath and in particular correlated multipath should be avoided. LOCA should be respected.	GNSS
S7	Minimum separation and specific geometric arrangement between GNSS RRAs: related to the ionosphere gradient monitoring performance	GNSS
S8	Climate conditions and seasonal variations: o Areas where snow tends to build up should be avoided. o Areas used for snow deposits must be avoided, or these must be moved. o Possible flooding must be taken into account	GNSS (VDB)
S9	Any potential airport expansion/modification plans	General
S10	Possible reuse of existing infrastructure	General
S11	Distance to public areas (related to RFI aspects)	GNSS

Table 3: Siting Restrictions

In general, the most restrictive criteria are the 5 km limit between the thresholds and the GNSS part of the ground station and the line-of-sight requirement for the VDB link. This is especially true for some large and complex airports like Munich international airport.

Figure 5-1: Munich Airport with 5 km circles centred at thresholds

Figure 5-1 above shows a map of Munich Airport including the third runway, with 5 km circles centred at each threshold. Due to the large footprint of the airport, the only area which is within 5 km from all thresholds is the area in the centre of the map. Possible locations for a GBAS ground station would be south-southeast of the south most runway, and west-southwest of the third runway. It seems infeasible to find sites for the VDB in these areas, which have line-of-sight to all runway surfaces.

Frankfurt and Toulouse are the airports which are subject to study in SESAR 15.3.6. After the opening of a new runway in the northwest in 2011, Frankfurt airport has increased its footprint and has become more difficult to cover with a single GBAS station. Figure 5-2 shows a map of Frankfurt, with 5 km circles centred on the thresholds. The north/south runway (RWY18) is only used for takeoffs. Therefore no circles are centred on the thresholds of this runway.

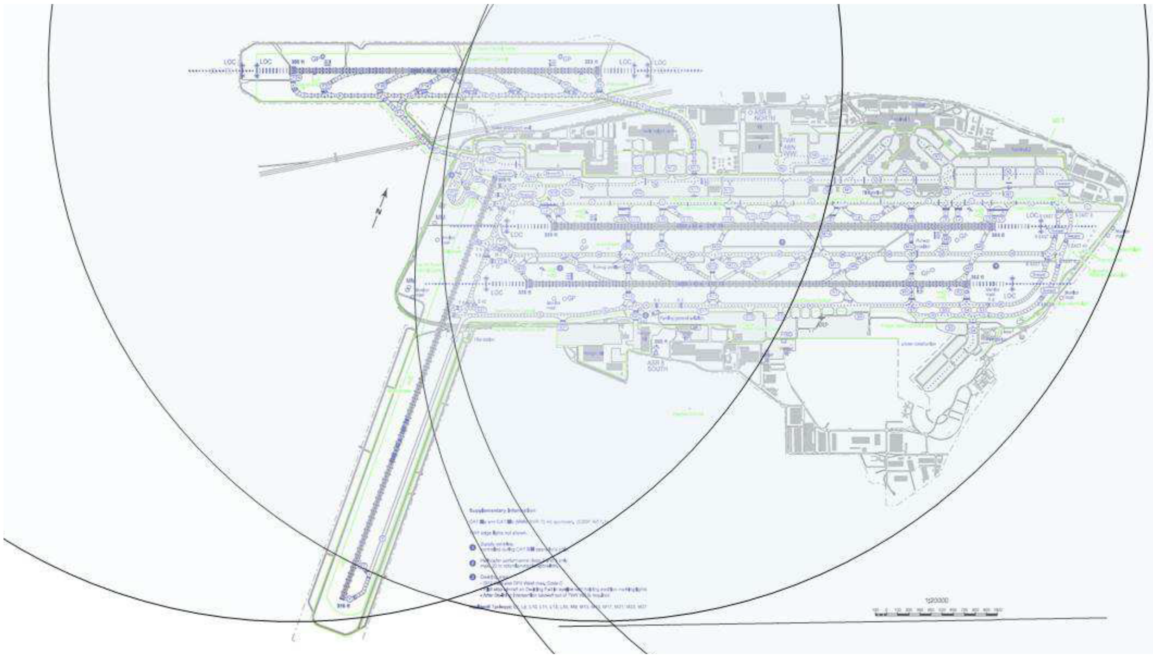


Figure 5-2: Frankfurt Ariport with 5km circles centred at thresholds

As can be seen from the figure above, the only possibility for siting a GBAS ground station within 5 km from all thresholds are in the middle of the airport. There are no candidate obvious sites in this area. The possible sites are at the middle marker for 07R (to the left of the southernmost runway, and along the eastern part of 07L. The marker position would need a trade-off since it is slightly outside the 5 km circle for two of the approaches. The site along the east of 07L is within the 5 km limit from all 6 approaches, but it has some other challenges:

- Being located close to the runway, it is prone to shadowing from approaching and departing aircraft
- There is no line of sight to the two southernmost runways, complicating VDB coverage.

Munich and Frankfurt are thus examples where it may be complicated to provide CAT III services to all approaches with one GBAS station. A more benign ionospheric model for these areas than the one which is the basis for the 5 km ICAO requirement may allow for some tradeoffs. A German iono model [60] to support this was developed and used for the type approval of a GBAS CAT I ground station in Germany. Based on this, the middle marker position may still be used to serve the six approaches.

Toulouse has a relatively uncomplicated layout where the 5 km criterion does not impose any challenge. It is therefore not addressed in detail here.

5.2 Radio Frequency Interference

Radio Frequency Interference (RFI) for GBAS CAT III has to be analyzed in two frequency bands for the VHF Data Broadcast (VDB) signal and the GNSS band.

5.2.1 VDB Interference

The VDB frequency can in principle be assigned in the VHF navigation band between 108MHz and 118MHz. This is a protected frequency band reserved for aeronautical radio navigation services. The Instrument Landing System (ILS, lower VHF nav band 108MHz to 112MHz) and the VHF Omnidirectional Range (VOR, upper VHF nav band 112MHz to 118MHz) operate in the same band as GBAS. Interference is typically avoided by Europe-wide frequency coordination. Fixed coordination criteria for GBAS ↔ ILS do not exist in the ICAO Annex 10 Vol. I. SESAR 15.3.6 T024 has developed draft criteria that were provided to ICAO NSP in 2011.

During siting the location of the VDB antenna will be fixed. The position of the antenna (together with the VDB antenna characteristics) are input for the frequency planning process that tries to find and coordinate a VDB frequency. Therefore, the final VDB frequency is typically unknown during site qualification. As part of the site acceptance the VHF band may be checked during GBAS ground testing as part of the unwanted emissions testing [25], §4.2.28. If a second GBAS ground station is operating on the same VDB frequency within the radio horizon it would make sense to check the VDB interference level on all eight slots of the assigned frequency as well. Similar checks in the VHF nav band should be performed during site qualification to confirm that there are no unknown frequencies or slot occupations in this band (e.g. harmonics or intermodulation products from other frequency bands, e.g. FM radio broadcast stations).

5.2.2 GNSS Interference

One can distinguish between spoofing (feed GNSS receiver false information so that it computes an erroneous time or location) and jamming (prevent a position lock of GNSS receivers). In this context we will exclude intentional spoofing by military forces or terrorists and concentrate on devices that are publically offered e.g. via internet. These devices produce different type of GNSS interference. One can distinguish between RNSS-like interference and non-RNSS like interference. ICAO Annex 10 Vol. I includes requirements for non-RNSS like signals. GNSS receivers have to operate with a given performance within certain limits of CW interference, noise like interference, and pulsed interference. Interference above these limits shall not cause misleading information [9], 3.7.3.4. RNSS-like interference is not explicitly addressed by ICAO Annex 10 requirements. The foreseen protection is spectrum management and regulation by the states that provide GNSS services in their airspace.

In the early days of GPS the number of interference events was very limited. In very rare cases military sources, failed receiving antenna amplifiers or devices producing broadband noise were found to be sources of GNSS interference.

In our days, GNSS interference is becoming more and more a challenge in the implementation of GNSS based services in aviation [33], [46]. Due to the success of GNSS in many modes of transport and other applications including services for vehicle tracking, people tracking, and road charging the market for GNSS interference devices is increasing dramatically. Such devices are sold as Personal Protection Devices (PPD) and they are very cheap (a few tens to several hundred Euros). Most of these PPDs are a kind of CW or narrow band interferer. Many of them are small enough to be plugged into a cigarette lighter inside a car. A GNSS receiver installed in such a car or truck will not be able to track any satellites. GNSS receivers in other vehicles close by or fixed installations close to such a road are likely to be affected as well. This scenario can cause GBAS loss of availability and continuity [45]. In Europe it is forbidden to use such interference devices but unlike in Australia it is allowed to sell, to buy and to possess them [34].

A different type of interference is produced by devices that amplify and delay or generate RNSS-like signals. RNSS means Radio Navigation Satellite Service and is the ITU expression for the frequency band where the GPS L1 frequency belongs to and that is reserved for satellite to earth services. The devices that produce RNSS-link interference do not just degrade availability and continuity but have the potential to cause integrity problems [40]. So far the only foreseen protection against interference from these devices in ICAO SARPs is regulation. In Europe regulations are in place or are under development for GNSS repeaters, see references [35], [36], [37], [38], and [39], as well as Pseudolites [47], but regulation has its limits in deregulated markets.

GNSS repeaters are becoming popular for professional applications like aircraft maintenance at airports. GNSS repeaters retransmit the received GNSS signals inside buildings. They enable to operate and to test GNSS equipment inside e.g. a maintenance hangar, an emergency service garage, a production line or a supermarket that sells navigation devices. These buildings are not shielded and therefore the amplified and delayed GNSS signals of the repeater can be received outside the buildings as well [34]. Outside the repeater signal interferes with the direct signals received from the satellites. GPS receivers are designed to receive RNSS signals on the GPS L1 frequency and they currently have no means to detect a repeater signal. Therefore they may provide wrong position information without timely warning.

A similar interference can be caused by pseudolites. These are ‘pseudo satellites’ placed on the ground to provide additional ranging sources. Pseudolites complement the signals received from the satellites in space and can provide better geometries for a GNSS position solution. Whereas ICAO is no longer supporting these devices (in ICAO terms called ground based ranging sources) they are installed and used in Europe to build up Galileo test beds (e.g. GATE in Berchtesgaden, Sea Gate in Rostock, aviationGATE in Braunschweig, railGATE and automotiveGATE in Aachen).

5.2.2.1 Personal Privacy Device Scenario

In 2011 ION and IEEE papers were published that help to characterize the RF output of PPDs provided on the market [12], [13]. Most of the devices are generating interference by linear frequency modulation of a single tone. Sweep ranges up to ±40MHz around GPS L1 frequency with sweep times in the range of µs to some ms characterize the modulation.

For a cigarette lighter device with an output power of 9.5mW over 20MHz bandwidth (9,7dBm) and no additional attenuation this would result in a necessary separation in the order of 300m to continue GPS L1 tracking and a necessary separation of about 1km to start GPS L1 acquisition [12]. For the worst case jammer with 642mW output power (28dBm) the separation values are 6.14km for GPS tracking and 8.67km for GPS acquisition [12]. Attenuations that would help to limit the affected area are:

- 3dB loss due to linearly polarized signals generated by the antennas of simple interference devices received by right hand polarized GPS antenna [12],
- 10dB maximum attenuation due to bad orientation of the interference device antenna [12],
- 22dB vehicle attenuation [14].

In reference [13], a mathematical model of the analyzed jammers is given that could help manufacturers to analyze the effects of such interference. In [15], an intermediate report about the GBAS RFI problems at U.S. airport is presented. The number of interference events is reported to be in the order of several events per day. Every two days the interference events were severe enough to cause a GBAS CAT I ground station installation to shut down. The airport is surrounded by highways on all four sides. In-car jammers (PPDs) are causing these problems but the culprit could only be caught in one case. The number and the speed of vehicles passing by on a 14 lane highway is too high to identify and stop cars equipped with these jammers. Possible countermeasures for such a scenario discussed in the report are

- increase separation of GNSS reference receivers to highways,
- lower GNSS reference antenna height (increasing the antenna height to make use the antenna attenuation for low elevation angles did not improve the situation),
- add ½” mesh to airport operations area fence to better protect the GNSS reference antennas from GNSS RFI,
- improve GBAS ground station algorithms to survive a limited time with only two reference antennas.

As the above-mentioned improvements were defined for GBAS operation according to GAST C, it is not yet clear whether the above-mentioned solutions can be fully applied also for GAST D. For instance, it is currently not fully clear if a GAST D operation with only two antennas in the ground subsystem is possible. This results from the fact that the interface between air and ground refers to GAD C3 performance. Furthermore, certain monitors may not be able to work with only two receivers while still maintaining the allocated integrity and continuity. Another point may evolve when considering also to enhance the inter-antenna separations in order to limit the influence of the jammers to single antennas. This needs to be carefully assessed with regard to the GAST D ground subsystem ionospheric monitor, as its performance will necessitate to maintain certain baseline(s) length(s) and orientation.

5.2.2.2 GNSS Repeater Scenario

According to the European standards, legal GNSS repeaters should be restricted to professional applications [7]. Mobile applications are not allowed. Exceptions are military transporters and military aircraft that may be equipped with GNSS repeaters.

Legal GNSS Repeaters
European standards for GNSS repeaters allow a maximum of +45 dB total gain (including antenna gain) or alternatively 48 dB (the maximum of the antenna gain, amplifier and an assumed maximum feeder loss of 3 dB). They limit the level of the repeater output signal to -77 dBm EIRP. A maximum gain of +45 dB equates to a GNSS protection distance of around 10 m for a -160 dBW GNSS signal [6]. Therefore a fixed legal repeater installation (operator has an individual frequency license from the national spectrum management authority) which copes with the European standards should not cause a problem for GBAS.

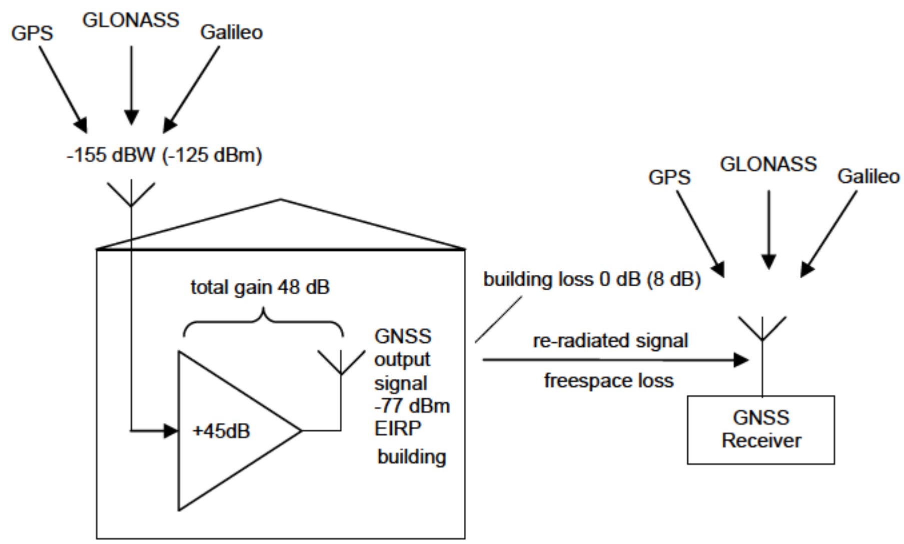


Figure 5-3: Proposed European technical standard for GNSS repeaters

Illegal GNSS Repeaters
In 2010, an illegal high power repeater installation was found at an international airport in Germany [3]. It was installed in a new aircraft maintenance hangar in about 320m distance from one of the four runway thresholds. It caused ground proximity warnings of commercial airliners during takeoffs. In addition the pilots in some instances observed GPS-INS mismatch warnings. A detailed analysis of the airline and the equipment manufacturer showed that the build in GPS receivers were interfered.

Measurements of that illegal GNSS repeater installation by the national spectrum management authority together with the air navigation service provider were performed. A comparison of the measurements with the European standards shows that the gain and the output power of that installation was at least 28 dB too high.

Such a GNSS repeater with -49dBm EIRP could in theory disturb receivers up to a horizontal distance of 540m. This value is calculated by assuming free space loss of the GPS L1 frequency and the assumption that an interference signal 10dB below the minimum GPS signal power of -158,5dBW = -128.5dBm will not degrade the performance of a GPS receiver.

A GBAS ground station with its precisely known GNSS reference antenna positions and integrity monitors should be able to detect RNSS interference caused by a repeater. More information is needed, as in principle a repeater should be far enough away, so that the GS detects the erroneous information when the signal is strong enough to be tracked by the GS, however such information is not available today from manufacturers. Ground stations have several monitors and mechanisms that may detect repeaters in the case if one or more of the receivers are affected by the re-broadcasted signals. Such monitors and mechanisms may include:

- Signal-to-noise monitoring
- Signal Deformation Monitoring
- Acceleration monitor
- Step detection/carrier smoothed code test
- B values/B-value monitoring

A deliverable from WP15.3.4 task 6.4 will provide information from an ongoing study related to use of repeaters in the context of GNSS. To avoid performance degradation caused by a GNSS repeater

- interference measurements during site survey, and
- separation of GNSS reference receiver antennas from potential repeater locations would help. Special receiver or ground station algorithms could contribute to a better detection of interference or to minimize the effects of interference.

The estimates above show that the affected area of such a repeater is still small compared to the whole airport operational area. A GBAS ground station is typically installed at remote positions (see above). Therefore there is a certain risk that the GBAS ground station cannot receive the GNSS repeater signal and cannot protect the aircraft.

For approaching aircraft the necessary vertical separation from such a repeater may be smaller than the horizontal separation. Due to the fact that the GPS antenna of the aircraft is installed on top of the fuselage there is an attenuation of signals received from the ground directly underneath the aircraft of 10dB maximum for wide body aircraft [41], Table 0-1. Such a scenario would result in a minimum vertical separation between a repeater and approaching aircraft of 170m. If such a GNSS repeater can be located at the highest possible location (CAT I OCS with 1:34 slope used for this calculation) underneath a typical approach path (3° GPA, 15m TCH) the airborne receiver could be affected during a final approach starting at a distance of 6662m from threshold.

5.2.2.3 Summary of Radio Frequency Interference

The given examples demonstrate that regulation cannot protect one hundred percent against interference above and beyond the generic scenarios that were defined in ICAO Annex 10 more than ten years ago. The equipment should contribute to a safe and robust GBAS operation.

RNSS-like interference was a very rare event in the past but has become a more frequent threat. At least in one U.S. location, several events per day were observed for a GBAS installation on an airport with reference antennas close to a very busy highway. In this case the national spectrum management authority was not able to find and eliminate all interference sources in cars on that highway. ICAO Annex 10 requires that integrity has to be ensured for RNSS-like interference. Full performance is only guaranteed for environments within the defined interference limits. In case of RNSS like interference the availability and continuity can decrease so far that the operation of a GBAS ground station is difficult.

Non-RNSS-like interference signals are currently not explicitly addressed in the ICAO Annex 10. At least one national spectrum management authority assumes that 90% of the installations (that would need an individual frequency license) are illegally operated even by professional operators. Depending on the architecture GBAS ground stations should have a good chance to detect effects caused by these devices. Airborne GBAS CAT I receivers do not provide standardised mechanisms to protect against interference threats that may e.g. arise from the use of ground based GNSS repeaters. Whereas in the GBAS CAT I case the visual segment below decision height offers a chance for the pilot to detect and correct the aircraft position or initiate a missed approach this is not the case for future GBAS CAT III operation. Safety assessment work could analyse which counter measures (e.g. on aircraft integration level) could contribute to a safe operation.

Discussions on ICAO Navigation Systems Panel (NSP) level have taken place but no decisions were taken. Inputs form the technical standardisation bodies (RTCA and EUROCAE) were requested by NSP. Activities around the world aim to collect more information about the interference devices and possible scenarios (e.g. task 6.4 in SESAR 15.3.4 'GNSS Baseline Study', results expected in the second quarter of 2013). But so far there are no standardised threat models for interference above and beyond the models in the ICAO SARPs.

To minimize the number of interference events and to limit performance degradation under these circumstances GBAS ground station architecture and airport installation could contribute by

- increasing attenuation in the direction of the interference source (distance, fence/wall/obstacles, reference antenna characteristic),
- making GNSS receivers robust against interference,
- improving GBAS ground station monitoring and internal redundancy management to detect and if possible mitigate such threats (the approach taken for GAST C ground stations may not be appropriate for GAST D),
- site measurements over longer time periods (e.g. one week) to detect non-permanent interference sources in an early stage.

5.3 GNSS Multipath and diffraction

As mentioned in 4.2.3 with correct siting the ground reflection will be the main multipath source for a GBAS installation.

Within this section, more detailed information on multipath causes and resulting effects for GBAS will be discussed. The evaluation of multipath will be subject to discussion within this section and a CMC based methodology based on the one used for CAT I and described in ED-114(A) ([1]) is given. Multipath influences with regard to CAT I are discussed in [1]. The present section expands these explanations Differences between GAST C and GAST D will be mentioned.

5.3.1 Multipath considerations

Under nominal conditions multipath is the largest error source for GBAS. Multipath errors result independently from airborne and ground subsystems multipath environment and the used technology. Multipath errors are uncorrelated between air and ground and the GBAS differential processing will therefore not reduce them.

Multipath errors will result when the GBAS equipment processes combined direct and reflected signals. With regard to the ground subsystem multipath errors result from signals which were reflected on objects in the vicinity of the ground subsystem reach the GNSS antenna and pass through the ground subsystem processing and affect the GBAS pseudorange corrections.

Mitigations against multipath errors are (listed in preferable order of applicability):

- receiver / antenna technology
- correct siting
- masking of multipath reflectors by elevation / azimuth mask as part of the siting process

- sigma_pr_gnd bounding
- monitoring
- operational procedures (i.e. clearance to pass, separation of transient objects, etc.)

The first two bullet points characterize the mitigations with the largest influence. While the other mitigations protect from multipath influences their variation influences the availability and therefore need to be applied carefully together with an assessment on the resulting availability or operational influences.

The sigma_pr_gnd parameter is the key integrity parameter characterizing errors in the responsibility of the ground subsystem. During determination of the sigma_pr_gnd, D, it is verified that for 30s and 100 s PRCs:

- no direct (specular) reflections from permanent objects degrade the ground subsystem performance
- direct reflections from transient objects are limited to a single antenna at a time
- all remaining multipath effects are covered by the parameters forming the sigma_pr_gnd

Abnormal performance due to multipath effects would result under

- conditions leading to multipath errors on a single antenna such that bounding through sigma_pr_gnd is no more ensured.
    - These are observable in the B-values representing the single antennas error contribution. An appropriate monitoring has to ensure the detection of these errors.
- conditions leading to multipath errors which are correlated between the antennas and lead to a violation of the bounding by the sigma_pr_gnd-parameter can be further divided into:
    - Correlation of multipath errors between two antennas: These (can be) detectable by B-value based sigma-mean monitoring
    - Correlation of multipath errors between more than two antennas: These are not detectable by B-value based sigma mean monitoring. They need consideration in sigma_pr_gnd by allocating a certain amount of residual correlation as well as by siting, by ensuring compliance with the sigma_pr_gnd allocation.

The verification with regard to the 30 s PRC is to be performed having in mind potential adverse availability effects. These could stem from unrecognized differences in the multipath performance of the 30 s and 100 s PRCs. An integrity issue with regard to smoothing time constant difference will be prevented from the addition of the DL & DV values in GAST D ([6]).

5.3.2 Multipath sources & multipath effects

It needs to be distinguished between the multipath sources and multipath effects. The first is referring to objects having the potential to generate reflected satellite signals such that they reach the GNSS antenna(s). The second refers to the effects resulting from the reflected signal in the GBAS processing once they have reached the GNSS antenna. With other words, the resulting multipath influences in the GBAS pseudorange measurement depend on the reflection geometry and the technology (receiver & antenna,) used in the GBAS.

Sources of reflection are dependent on the geometry between the receiver and the obstacle. All of the following criteria need to be satisfied to produce multipath reflections:

- Snell's Law states that the angle of incidence of a propagated signal equals the angle of reflection. Thus, a ground reflection from a satellite at 10° elevation will enter the antenna at -10°.
- Fresnel Reflection Zone defines the area required to reflect a significant amount of signal power. Any reflector that is much smaller in surface area than a circle with a radius given by $R_{fresnel} = \sqrt{(0.19m * d)}$, where d is the distance between the obstacle and the reference antenna, will be sufficiently attenuated. If the angle of incidence is not 90°, the Fresnel

reflection zone will have the shape of an ellipse with the length of the semi-major axis given by $R_{fresnel}$ / sin(elevation angle). Objects in the direct signal path with dimensions smaller those defined by R, still can cause diffraction.

- Reflection Coefficient is a measure of the electromagnetic properties of a material. Metal surfaces will reflect signals almost perfectly, while the ground or vegetation will not reflect as much energy. The coefficient is mostly estimated from empirical data, and is also dependent on the surface roughness of a material and the angle if incidence of the signal. In the case of water, salt content has a strong impact, and ground coefficients can vary considerably depending on the moisture content or snow cover. For circular polarized signals further attenuation of the reflected signal can result from change in polarization. This happens for incidence angles larger than the Brewster angle.
- Rayleigh criterion is used to characterize the surface roughness. The surface roughness influences the amount of reflected signals that reach the antenna. For an electrically flat surface specular reflection will occur and thus a stronger multipath influence will result. For an electrically rough surface diffuse reflection will predominate. A rough surface can be characterized by the condition dH > 0.19/(8sin(elevation_angle)), where dH is the average height difference of the surface.

In context with the GBAS processing and more generally the chain until generation of the GBAS PRC needs to be considered for multipath error propagation through the ground subsystem:

- Multipath and object geometry with respect to Fresnel zone
- Reflectivity coefficient
- Incidence angle and polarization
- Antenna gain pattern difference between direct and reflected signal
- Receivers correlator and filter technology
- Relation between object size and distance and satellite motion
- Receiver tracking loop design
- Code carrier smoothing time constant.
- Averaging over the Ground Subsystem Antennas

GNSS signals can either be reflected or diffracted off the ground, buildings, vegetation and vehicles. GNSS reference antenna sites should be clear of any such structure causing distinct multipath errors. Sources of diffraction, such as metal edges of buildings, generally lie not far from the direct signal path between the satellite and the receiver, and are thus more easily identified. The amount of diffracted energy depends largely on the shape and the material of the edge. Even vegetation can cause some levels of diffraction. Diffraction is critical because it enters the antenna at a positive elevation angle and thus without much attenuation.

A first classification of multipath sources can be based on their mobility:

Fixed objects as multipath source:

- ground with varying reflection coefficient (ground surface material, incl. environmental condition): is primarily addressed by receiver / antenna technology and installation (treatment of ground below the antenna)
- shelter: is primarily addressed by siting
- airport buildings: is primarily addressed by siting
- vegetation, incl. possible effects from seasonal variation: is primarily addressed by siting and also by site maintenance

Transient objects as multipath source:

- vehicles (maintenance staff): is primarily addressed by operational procedures and maintenance procedures
- aircraft: is primarily addressed by siting, under special conditions (place restrictions) also operational procedures (ground traffic control) may help to mitigate the influence

A further classification can be based on the objects potential to cause specular multipath passing through the ground subsystem processing..

Possible objects causing specular multipath:

- Fixed objects with distances leading to a multipath delay inside the receivers multipath envelope (typically 155 m for narrow correlator E-L receivers). Code-carrier smoothing can only reduce the resulting effect, when the object size is sufficiently small.
- Transient objects with distances leading to a multipath delay inside the receivers multipath envelope (typically 155 m for narrow correlator E-L receivers). Besides the objects size influence on the code-carrier smoothing, also the timely behaviour is of importance.
- Ground below the GNSS antenna
- Up-sloping terrain

With up-sloping terrain, the ground reflection can reach the antenna with positive elevation angles. This happens if the satellite elevation is twice the slope angle (if the up-sloping terrain reaches directly to the antenna).

Mounting antennas as low as possible will reduce exposure to ground reflections. On the other hand, multipath sources causing delayed signals to enter the antenna from positive elevation angles are not tolerable at all, which may require the antenna to be mounted at a height sufficient to avoid the effect.

Rooftop GNSS antenna installation is not addressed within this document so the related siting criteria for such installation are out of scope.

The antenna gain-pattern difference between the directions of the direct and the reflected signal drives the ratio between the direct and reflected signal components. With reduced antenna susceptibility in direction of reflected signals the multipath errors can be reduced. For this reason a GBAS ground reference antenna should have a very sharp cut-off below its nominal tracking elevation.

Reflections can also induce a change in the polarisation sense of the GNSS signal, such that a single reflection is left hand circularly polarised instead of right hand polarised. This will typically cause 3 dB of attenuation for a right-hand circularly polarised (RHCP) antenna. If the polarisation of the reflected signal is changed, depends on the reflectors properties and the reflection angle. For angles larger than the Brewster angle the polarisation changes from right hand to left hand circular polarisation.

With regard to multipath geometry, the Rayleigh criterion can be used to characterize the roughness of a reflectors surface. From the roughness the reflection kind can be derived – either specular or diffuse. For a surface roughness larger or equal to $\lambda_{L1}/(8\sin\theta)$, with the carrier wavelength λ_{L1} and the satellites elevation angle θ, a rough surface will result. With the minimum elevation angle of 5° the surface roughness needs to be larger than 30 cm to allow for the predominance of diffuse multipath.

Reflections from moving vehicles such that they are modulated at a frequency greater than the tracking loop bandwidth are also not seen by a receiver. However, the effect of nearby vehicles at a momentary standstill needs to be considered as well.

Various technologies exist to reduce the effects of multipath, such as advanced reference receiver correlators and processing techniques, or antennas especially developed for GBAS GAD C. However, the best strategy is to avoid multipath effects at their source. In some cases, it may be possible to eliminate or modify the source. With regard to the further influences, the

- Signal properties, mainly the PRN code properties, and the

- Receiver properties, mainly correlator and discriminator type and pre-correlation filter design

are relevant for the resulting multipath error (post receiver). With regard to the resulting GBAS multipath error, not only the influence on the code pseudorange measurement, but also the carrier phase measurement and the code-carrier smoothing filter properties have to be considered. With an wide correlator receiver the maximum multipath delay, that can pass through the correlation function is 1.5 chip lengths of the C/A code, which translates into 293 m. Not considering the influence of the pre-correlation filter, the maximum multipath error for a wide correlator receiver is 147 m. While for GAST C wide correlator receivers principally could be a choice for the usage as ground reference receivers, for GAST D only improved receiver correlator technology is considered. By using improved correlator technology, also improved multipath mitigation is achieved. With current GAST D prototype designs, E-L 0.1 chip narrow correlator receivers are considered. These limit the maximum multipath error as well as the multipath delay. A 0.1 chip E-L receiver limits the maximum multipath error to approximately 15 m for a reflection coefficient of 0.9 and for infinite bandwidth. As no receiver has infinite bandwidth the pre-correlation filters influence needs to be considered. The pre-correlation filter increases the resulting multipath error somewhat in dependence on the filter properties. Compared to wide correlator technology the multipath delay of a reflected signal able to pass through the receivers autocorrelation function is much shorter. As previously stated the maximum multipath delay to pass within the receivers multipath envelope is 310 m. Thus with E-L and 0.1 chip narrow correlator technology the distance to all fixed obstacles should be greater than 155 m. Transient objects have to move or when standing still then only for a time period shorter than the smoothing time constant (30s for GAST D) in order to minimize their influence. The remaining multipath error outside the multipath envelope, i.e. for multipath delays larger 310 m is much smaller than for multipath delays inside the multipath envelope. The size of the remaining error depends on the PRNs autocorrelation properties and can reach 1.5 m.

An example for the possible code multipath errors vs. path length difference for a 0.1 chip narrow correlator E-L receiver incl. pre-correlation filter is shown in Figure 5-4 for PRN22. The pre-correlation filter leads to increased maximum multipath errors compared to the theoretical ideal. The multipath error shows rapid changes over the path length difference, since the resulting multipath phase angle changes as a function of the path delay. Since the multipath error is much smaller on the carrier phase measurement code-carrier smoothing can reduce resulting multipath errors. In order to achieve an error reduction the length of the multipath event – and thus object size - needs to be shorter than the code-carrier smoothing time constant. Or more precise the frequency of multipath variations should be higher that the corner frequency of the carrier smoothing filter. The multipath variation frequency depends on the geometry between reflector and receiver with regard to the satellite signal. The larger the size of the object or/and the closer it is, the lower the frequency. The topic was also discussed in the light of the smoothing ration between 30 s and 100 s smoothing in D03, App. A ([6]). In order to assess a GNSS antenna site with regard to possible multipath reduction by code carrier smoothing an assessment of identified multipath objects vs, reduction potential by CCS has to be performed.

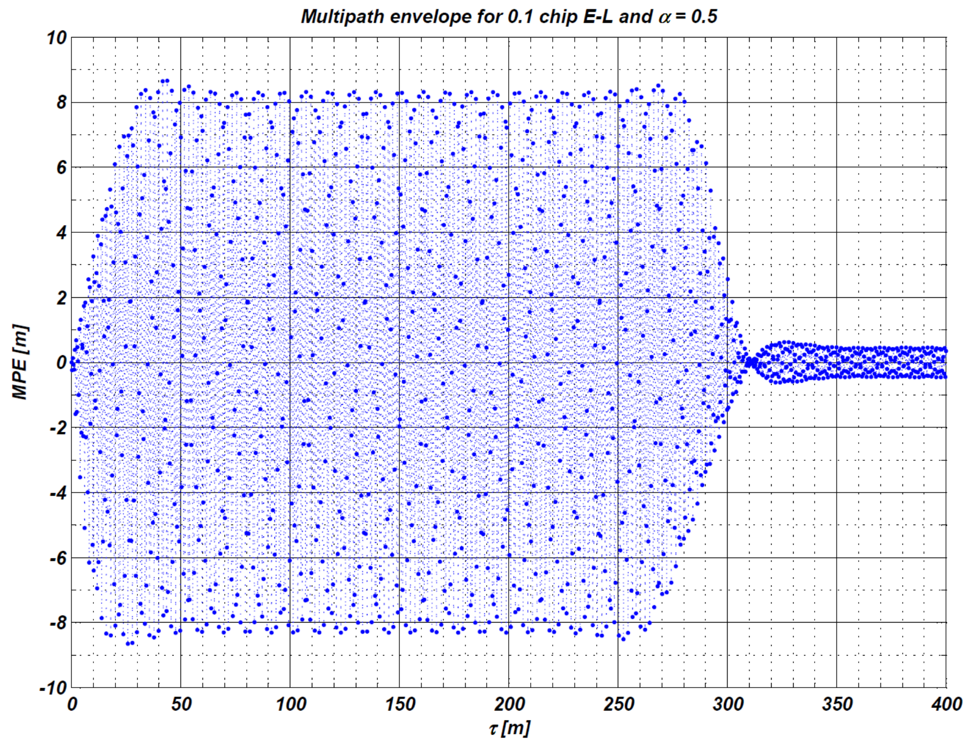


Figure 5-4: Example of the range of resulting multipath errors for a narrow correlator receiver incl. pre-correlation filter influence and assuming a reflection coefficient of 0.5, simulated for PRN22.

The GNSS reference antenna sites shall be chosen such that no multipath from direct reflections can influence the range measurements. The required minimum distances will depend on used correlator technology. The ground reflection is suppressed by antenna technology in two ways: the antenna provides a large sensitivity difference for signal reaching the antenna with positive and negative elevation angles. The antenna pattern for signals reaching the antenna from below is stochastic (different between the antennas of a ground subsystem).

It becomes obvious that the siting criteria with regard to multipath mitigation strongly depend on the used receiver & antenna technology. Therefore, different receivers will lead to different siting criteria, i.e. LOCA definitions.

In general, the GNSS antennas shall be mounted as close to the ground as practically possible to reduce the impact of multipath reflections from the ground. However, the mounting height will be a trade off between required sky view, impact from nearby objects (for example a fence, other antennas, animals) and snow conditions on one side, and possible reflections from the ground on the other side. The GPS antennas should not be mounted on a highly reflective surface, such as a metal roof.

When antennas are mounted in the terrain, ground reflections are normally not an issue, and the antennas shall be mounted high enough to avoid being covered by snow during winter, or being shadowed by vegetation.

If the antenna is mounted on a hill, or on a rooftop, this may increase the exposure to ground reflections. On flat roofs, it is usually better to mount the antenna a few meters from the edge, rather than on the very edge.

Calm seawater will cause higher susceptibility to ground reflections. If the horizontal distance from the antennas to visible seawater can be made longer than 12 times the height above sea level (or correspondingly, the sea should not be visible below minus 5 degrees elevation), this will minimize sea reflections for satellites above 5 degrees elevation.

5.3.3 Multipath evaluation

The multipath assessment in the context of siting is done during the siting process to check

- if it is feasible to install a reference antenna at this site from a performance point of view (expectable sigma_pr_gnd at this site)
- to determine multipath related sigma_pr_gnd parameters and possible multipath masking at this site

The evaluation of the multipath environment is necessary

- to show compliance with manufacturer system performance derivations
- to show correct ground station siting
- derive site calibration parameters

Multipath measurements are part of the siting process. They are of relevance in assessing the accuracy performance expressed by the GAD , as well as in the derivation of the integrity performance expressed by the broadcast sigma_pr_gnd [3]parameters. It has to be noted that differences between the multipath evaluation for site calibration and performance determination exist. The different focus between site calibration measurements, to identify multipath sources regarding the derivation of sigma_pr_gnd parameters, and the assessment of the nominal accuracy performance, expressed by the GAD, leads to some differences in the applied processing. For instance the GAD assessment is performed over all reference antenna / receivers simultaneously, while multipath assessment in a first step is performed on a per antenna / receiver basis.

The multipath assessment is performed at a stage prior to installation of the ground station. It is part of the site survey, or more specific, part of site qualification.

It is necessary to perform the assessment at all candidate sites for each reference antenna. It is furthermore important to use the same antenna and receiver combination with similar mounting and installation as will be used for the ground station. The multipath measurements shall be performed at each antenna site using the same antenna / receiver as is used in the GBAS ground subsystem.

It should be considered whether the mode of operation of the airport can have impact on the multipath seen by the ground station. It should be taken into account in the multipath evaluation that changes in the usage of runways, runway directions and taxiways, may also lead to changes in the multipath environment of the ground station..

The preferred methodology for multipath determination in the context of GBAS ground subsystem siting is by using Code – Minus – Carrier (CMC) observables of the receiver / antenna combination together with accompanying dual frequency measurements from supporting dual frequency receiver/ antenna placed near the reference antenna / receiver combination.

The following aspects must be considered when estimating multipath characteristics based on Code-Minus-Carrier (CMC):

- Non-Gaussian distribution
- Estimation uncertainty
- Seasonal- and weather changes (humidity, snow, ice)

[3] The index indicating the GAST C or GAST D is omitted as the following statements are valid for sigma_pr_gnd,C and sigma_pr_gnd,D

- Signal level

In order to ensure that correlated multipath is not present, a dual-frequency logging campaign should be carried out. These measurements are based on simultaneous measurements with all reference receivers / antennas of the GBAS ground subsystem. This can be done during siting if correlated multipath is suspected or during site acceptance if one is relatively confident that the level of correlated multipath is acceptable.
If performed during site acceptance the risk can arise that the GBAS station must be moved if correlated multipath is detected. Alternatively it may be possible to mask out the direction from which correlated multipath is detected if the availability performance is ensured. Therefore the typical approach is to perform a multipath assessment at each antenna site first, then to install and then to perform the performance assessment (GAD test) to confirm the site selection. Another measurement step might be necessary to determine/confirm values to configure the GS. This would be performed after installation prior performance assessment.

Estimation of correlated multipath is done in a similar way as the multipath measurements by merging together data from the GBAS ground station antenna/receivers with data from a dual-frequency receiver in the vicinity of the GBAS ground station antenna. The two main contributors to correlated errors for GBAS receivers are correlated multipath and ionospheric errors. The measurements to determine the multipath correlations have to be performed during a period with calm ionospheric activity. Then it is possible to correct the CMC observables with a common ionospheric term from a single dual frequency antenna / receiver. A second dual frequency antenna / receiver can be used to determine the absolute ionospheric gradient during the measurements. The second receiver might be also useful to enhance the available dual frequency measurements.[4] The correlation between the reference receivers is then estimated by using the Code-Minus-Carrier (CMC) observable with corrections for ionospheric divergence based on the dual-frequency measurements.

No simple techniques exist for the identification of multipath sources. Multipath errors can be identified by collecting dual frequency range measurements and producing ionospheric error free code minus carrier residuals or by using other suitable tools. These measurements should be verified by taking data over multiple days, using representative equipment and processing. This will identify which satellites are affected by multipath when transmitting from a specific range of azimuths and elevations. While these measurements are typically performed during site qualification, it may be helpful to conduct some preliminary tests during site selection to verify the severity of suspected multipath sources, thus allowing to assess the feasibility of a particular candidate location.

5.3.3.1 GNSS receivers correlator function based principles

Besides the CMC methodology, multipath assessments principally can be based on other measurement principles. Well recognized are multipath measurements based on direct observation of deformations of the receivers autocorrelation function. Two well-known examples for such principles are:

1. Multipath Estimation Delay Locked Loop (MEDLL)
2. A-Posteriori Multipath Estimation (APME) (Septentrio)

Both mentioned technologies make use of additional correlator points in order to measure the autocorrelation peak deformation due to multipath. Details on both technologies can be found in [51] and [50] respectively.

The advantage of both principles is that they would be principally capable to output the multipath components as amplitude of the reflected signal, multipath delay and multipath phase – meaning the

[4] To date GPS dual frequency measurements are obtained from L1 C/A and L2 semicodeless P code measurements. The semicodeless tracking provides a poor tracking performance, and is therefore very sensitive to cycle slips, loss of lock and provides bad C/N_0 values. Therefore the number of usable samples is limited. This is especially the case at low elevation angles. But with respect to multipath and possible multipath correlations this is the region of interest.

components as 'seen' by the antenna. These components could be transferred into resulting multipath errors with knowledge of the receiver technology. Thus, the multipath measurement would not have to be performed with the receiver used in the ground subsystem. The direct observation of the multipath components may allow for better comparability with simulations.

However, the measurement quality depends on the spacing of the additional correlators and with it there follows the potential for unequal measurement quality of the multipath components over the entire correlator range. Furthermore the necessary transfer into resulting multipath errors produced by the ground receiver technology is disadvantageous.

For this reason, these principles are considered as special purpose methodologies, having the potential to support special multipath investigations and therefore are out of scope here with regard to general GBAS siting.

5.3.3.2 CMC-Analysis

5.3.3.2.1 Overview & CMC analysis options discussion

Within this section an overview of the CMC analysis will be given, as this methodology is seen as the one commonly used for GBAS related siting multipath evaluations.
However, the detailed methodology used for CMC analysis can vary in some points. Therefore it is envisaged to achieve a certain degree on commonality in order to achieve comparable results.

Regarding the multipath components in pseudo-range measurements it is distinguished between two kinds of multipath:

- *specular* multipath arising from discrete, coherent reflections from smooth surfaces, this component is included in M, as it has a deterministic appearance and

- *diffuse* multipath arising from diffuse scatterers and sources of diffraction. Due to this diffuse property its appearance is noise like. The underlying effect are reflections from rough surfaces and thus a principally deterministic process with stochastic properties.

The CMC linear combination usually contains:

- twice the ionospheric delay
- the specular multipath on code measurement
- the phase ambiguity
- code noise
- receiver tracking errors
- carrier phase noise
- carrier phase specular multipath

In the remaining term the phase measurement error, the carrier phase noise and the carrier phase multipath are negligible. The classical way described in literature to remove the phase ambiguity is by averaging, assuming the observation time is kept long. The code measurement error can be minimised by averaging over all receiver channels.

The classical way to determine the ionospheric delay is by using dual frequency measurements.
The drawback of simply removing the ionospheric delay using the pseudo-range based calculation is the increase in noise.
The carrier phase based ionospheric term however suffers being ambiguous. A bias between the code based ionospheric term and the one obtained from the carrier is introduced by the carrier phase

ambiguity. Therefore a combined processing, combining the advantage of being unambiguous from pseudo-range based processing and the advantage of very low noise of the carrier phase based processing can be used. Such a combination could be based on complementary Kalman filtering. As long as no loss of lock occurs, the bias can be determined from the mean of the difference between code and carrier ionospheric residuals. A loss of lock might result in a new bias (depends on the receiver) and therefore the mean of this subpart would have to be evaluated.

However, a further disadvantage of dual frequency processing to date is the lack of a commonly usable second frequency in aeronautical frequency bands. Therefore, in most cases semicodeless tracking of L2P code is used. Due to the semicodeless tracking, these measurements show very low C/N_0 ratios and very poor tracking performance. This can drastically reduce the number of usable samples, especially in the low elevation angle range, which is of special interest during siting. In addition, L2 is not a protected frequency. Therefore, interference by other radio services may prevent L2 tracking at all. This situation will change with the wider availability of L5 / E5a/b signals, but these are currently not widely available.

The reduced number of samples will result in data gaps. When measurements from a second dual frequency receiver in the vicinity of the first one and normal ionospheric conditions can be assumed, these gaps might be filled. Alternatively, an interpolation scheme might be a choice to cope with such gaps.

In order to avoid this drawbacks another often-used option is based on single frequency observables only. Such a processing is based on high pass filtering of the raw CMC observables. The high pass filter can be based on:

- linear regression filter (approach proposed in [53] and also used during initial GBAS CAT I analysis described in [54]). The advantage is as with FIR filters the frequency independent group delay. Furthermore principally no high frequency cut off is evident and thus there is principally no timely correlation influence from transient effects is evident.

- FIR filtering (approach used in PEG, described in [55]), advantage is that it is possible to use filters with frequency independent group delays. However, care must be taken to use a gate on the filter response in order to suppress the timely correlation influence from transient behaviour. The gate length depends on the filter type.

- Polynomial fit: this approach can be considered of a special case of FIR filtering, as over the entire dataset the ionospheric part in the CMC observable is approximated by a polynomial. The corner frequency can be interpreted to be represented by the order of the polynomial. In principle very good results can be obtained, however, care must be taken with the order of the polynomial in order not to remove too much multipath. The methodology is suitable for calm ionospheric conditions.IIR filtering: since these filters have a frequency dependent group delay they are not useful for this processing and thus are not considered here.

- Furthermore it is possible to use least square based approaches for explicit determination of single frequency iono removal.

The major drawback of the single frequency evaluation schemes is that the ionospheric delay is not removed from the CMC observables, but a low frequent component assumed to contain mainly the ionospheric delay – it is not known to which extent the ionospheric delay is removed.
In [69] it can be found that for coherent E-L code discriminators the average code multipath error is non-zero and positive. This multipath contribution would not be evaluated when removed by a single frequency scheme. In general, every influence on the CMC observable resulting from the high pass filtering influence of bias removals by averaging should be minimized.
For this reason the preferable processing should be based on CMC measurements from the reference antenna / receiver combination (which usually are single frequency) and a iono removal from

complementing dual frequency measurements using separate dual frequency receiver/antenna combination[5].

This obtained CMC measurement combination can also be used to characterise the $RMS_{PR\_gnd,XX}$ when it is built based on carrier smoothed pseudo-ranges. In case of GAST D two smoothing time constants are necessary – 30 s and 100 s. In the context of the above stated it is necessary to verify how the effectiveness of the code carrier smoothing on the respective antenna sites by measurement based assessment. This assessment is based on the comparison between the CMC result obtained from unsmoothed PR with the results for PRs smoothed with 30 s and 100 s.

With regard to the sigma_pr_gnd,X determination it is of special interest to assess the 100s CMC. If the 30 s performance adversely deviates from the 100 s performance the continuity can be impacted in two ways, either, the protection level exceeds the alert limit or the airborne monitoring using the difference between both position solutions, trips.

As the according ground contribution to the position domain difference in the airborne segment is also geometry dependent during siting both performances should be evaluated.
Besides the aforementioned consideration on determination of the sigma_pr_gnd, C&D, as a by-product the sigma_pr_gnd,30 can be determined from the CMC_30 results..

5.3.3.2.2 Proposed CMC analysis scheme to support GAST D siting

As stated before, the preferred way to perform the multipath analysis based on CMC observables is by the usage of additional dual frequency measurements.

It is recommendable to determine the CMC based multipath residuals based on unsmoothed, as well as with 30 s and 100 s code carrier smoothed pseudoranges. As previously mentioned the comparison will provide information on multipath influences, which are possibly reduced / removed by the code carrier smoothing. Furthermore, the influence of the different smoothing on the distribution of the CMC values can be assessed.

The following processing outline is based on [48] with some changes and additions.

1) The raw Pseudorange (PR) and Code-Phase (CP) observable from the reference receiver antenna are recorded together with Carrier-To-Noise (C/N_0) ratio and, if possible, other ancillary parameters such as elevation, azimuth and lock-time.
2) The CP observable on both frequencies from a dual frequency receiver (may be the reference receiver, if capable, otherwise a temporary receiver installation in close proximity) is recorded together with similar ancillary information. These observables are used to estimate the ionospheric error terms.
3) Both data sets are "pruned" to eliminate cycle slips, periods with C/N_0 below levels used by the ground subsystem equipment and short periods of visibility to not artificially increase the noise floor. The pruning has to be done with care, as relevant multipath may have similar signature. Considerable knowledge about the receiver types used and their multipath behaviour is a prerequisite.
4) A code-carrier smoothing filter with time constants of 30 s and 100 s is applied to the data from 1) to obtain smoothed values in addition to the unsmoothed PR (unsmoothed PR can be assumed to represent a smoothing time constant of 0.5 s.).
5) The CP observable is subtracted from the raw and the smoothed PR to obtain the raw CMC observation, which still contains ionospheric errors.

[5] Cases were the GBAS GAST D reference antenna is capable to obtain dual frequency measurements may exist. In such a case a signal split of the antenna signal to connect a dual frequency receiver in addition are possible when the determination of the performance for the antenna/receiver combination is not required (could be the case during site selection measurements).

6) From the two observables of step 2), the ionospheric error is determined by differencing and correcting with the relative iono effect
$D_{iono\_F1} = (P1_i-P2_i)^* f_2^2 / (f_1^2-f_2^2)$
The result is then delayed to account for the effect of the carrier-smoothing filter (one method is to use the carrier smoothing filter equation, but feed the iono estimate to both inputs).
7) On the resulting D_{iono} a gap analysis is performed and missing values for periods shorter than 15 min to be filled by interpolation. The purpose is to be able to assess the performance of the reference antenna receiver combination and to limited by the dependability on the availability of dual frequency carrier phase data.
8) Finally twice the result from step 6) is subtracted from the one of step 5) and any remaining biases (from the carrier phase ambiguity remaining after step 4) and/or an ambiguity effect remaining after step 5) are removed by removing the average over all receiver channels and removing the average over the contiguous[6] measurement intervals.

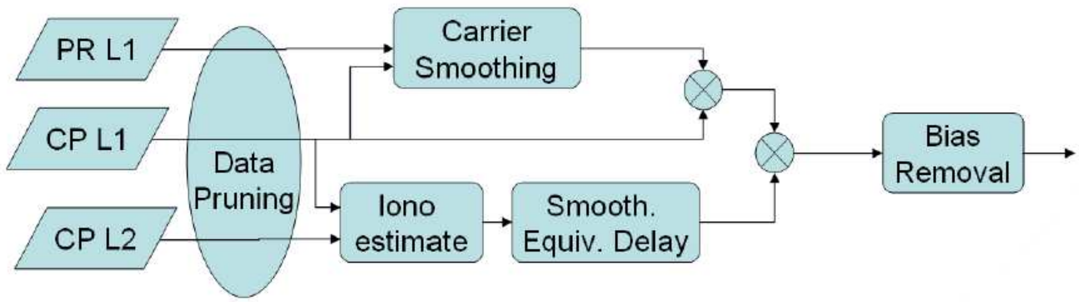


Figure 5-5: Determination of the CMC Observable [48].

Measurement data should be collected over at least consecutive 48h in the nominal configuration concurrently at all reference receivers, with another contiguous 24h interval in the degraded configuration, if used.
As multipath effects vary over time and may change with airport construction, a repeat analysis (summer/winter), if significant time has elapsed between initial site survey and final installation or after major changes in airport configuration (large buildings, traffic areas near receivers, etc.) may be advisable.

5.3.3.2.3 Examples for typical multipath evaluations

Examples for typical multipath evaluations will be shown below:

- A commonly used evaluation to obtain an initial performance overview is the depiction of the Root Mean Square (RMS) of the CMC values per elevation angle class, over the elevation angle. Given the distribution of the CMC values is of zero mean, the RMS represents the standard deviation of the CMC values. Therefore the mean per elevation angles class should be shown in addition. In order to ease the result interpretation, the GAD curves can be shown in addition. The RMS(CMC) vs. EL gives an indication on expectable (GAD) performance. It represents the measured combined multipath and noise performance. When measured over the recommended three days, it represents a snapshot of the overall performance range on the respective site, this has to be considered, when used as an input for sigma_pr_gnd determination. Depending on the methodology to establish the sigma_pr_gnd parameters, the RMS(CMC) result helps to verify the anticipated sigma_pr_gnd site parameters. An example for such a plot is depicted in Figure 5-6. The

[6] Depending on the used receivers typically after loss of lock, a different bias is experienced. A averaging over the whole dataset at once would lead to erroneous results. Therefore the bias removal based on averaging should be based on contiguous parts over the whole measurement interval. These contiguous parts have to be detected by an according detection scheme.

data stem from a field measurement campaign [56] and are valid for two single antenna measurements over several days. The difference between the left and right plot is the phase centre height. The mean per elevation bin is not contained in the example plots.

- The RMS(CMC) plot should be complemented by a representation of the number of used samples per elevation angle bin. In addition, the theoretically expectable number of samples should be given for comparison purposes. The number of measured samples, in comparison with the number of theoretically expectable samples per elevation bin, helps to identify satellite visibility or receiver/antenna tracking performance problems and furthermore helps to assess the quality of the obtained CMC evaluation results. For instance, it can be distinguished between missing samples on L1 using the reference antenna / receiver combination (these are then performance relevant) or if samples missing from Iono removal process. In the example plot in Figure 5-7 it should be considered that all measured samples were used, no sampling according to the code carrier time constants was performed to ensure statistical independence of the samples.

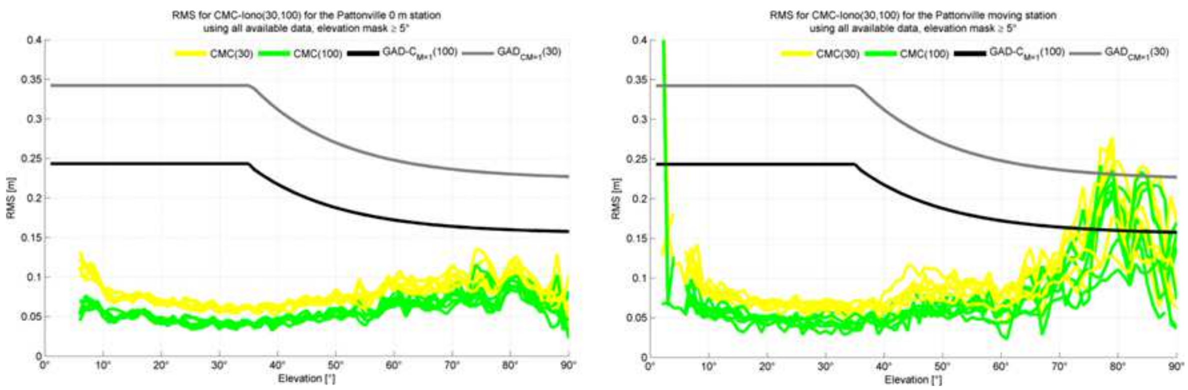


Figure 5-6: Example of RMS(CMC) vs. Elevation angle plot. Each curve represents the measurement result for one day (compare to [56])

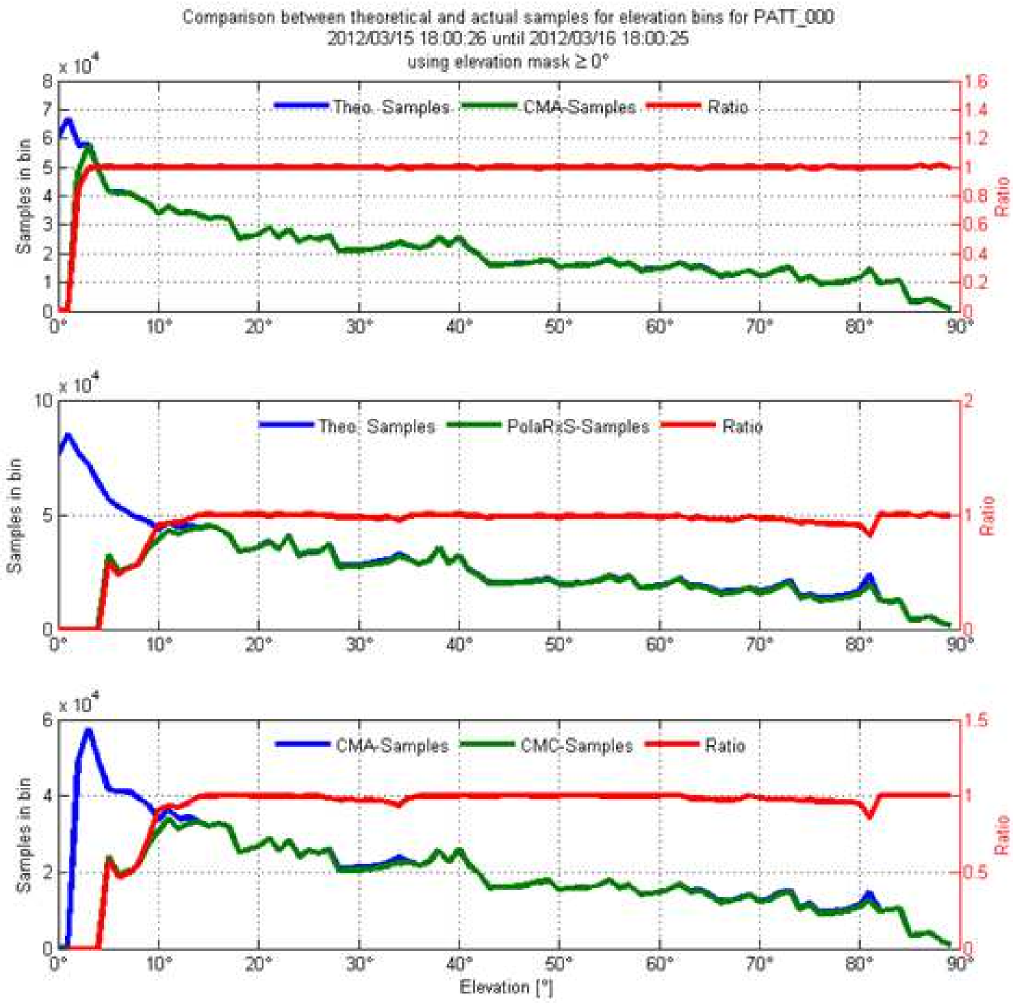


Figure 5-7: Example of Number of samples used for RMS(CMC) evaluation. The different figures represent the different measurement data sources (compare to [56])

An comprehensive overview on the multipath directions can be obtained by plotting the RMS(CMC) calculated per elevation/azimuth bin in a skyplot . A comparison against certain thresholds, which might depend on what the manufacturer sees as tolerable, can help in identification of areas potentially needed to be masked out. The bin width should be 1° in azimuth and elevation, but no more than 5° in azimuth. However, when used to mask specific areas, the manufacturer needs to define the bin resolution such that it complies with the resolution of the used mask. Bins with less than 5 samples should be disregarded. The code carrier smoothing process may mask multipath sources. To avoid missing this influence, unsmoothed CMC values should be assed in addition.

An example for the Polarplotis shown in Figure 5-9 and Figure 5-9. The first set of figures given in Figure 5-8 shows the measured CMC results for a single antenna on a single day, but with different smoothing time constants applied to the PRs. The reduction in RMS(CMC) is obvious. Furthermore no significant multipath directions can be seen for the smoothed results (30 s and 100 s). The higher RMS(CMC) values at high elevation angles primarily caused by the GNSS antenna characteristics. In comparison the unsmoothed result shows the expectable higher level of RMS(CMC). However, in addition also certain elevation azimuth regions with even higher RMS(CMC) compared to surrounding regions with same elevations can be identified ,In order to further assess these regions of higher RMS(CMC) in Figure 5-9 the RMS(CMC) from unsmoothed PRs are compared over several days.

Again, the plots represent the values from a single antenna. In these plots the region with increased RMS(CMC) is marked by a black ellipse. It becomes evident that the increased RMS(CMC) values in this region stay over the various days and therefore represent the multipath influence caused by a static obstacle. As this influence is not visible in the skyplots from the smoothed CMC, an in depth analysis should be performed to clarify the impact.

This analysis could be based on evaluation of the timely behaviour of the CMC values for the affected PRNs against a certain threshold. This will identify whether the result is not visible in the smoothed skyplot due to smoothing reduction of the multipath, or due to the statistical nature of the skyplot (since it depicts an averaged value per elevation-azimuth bin).

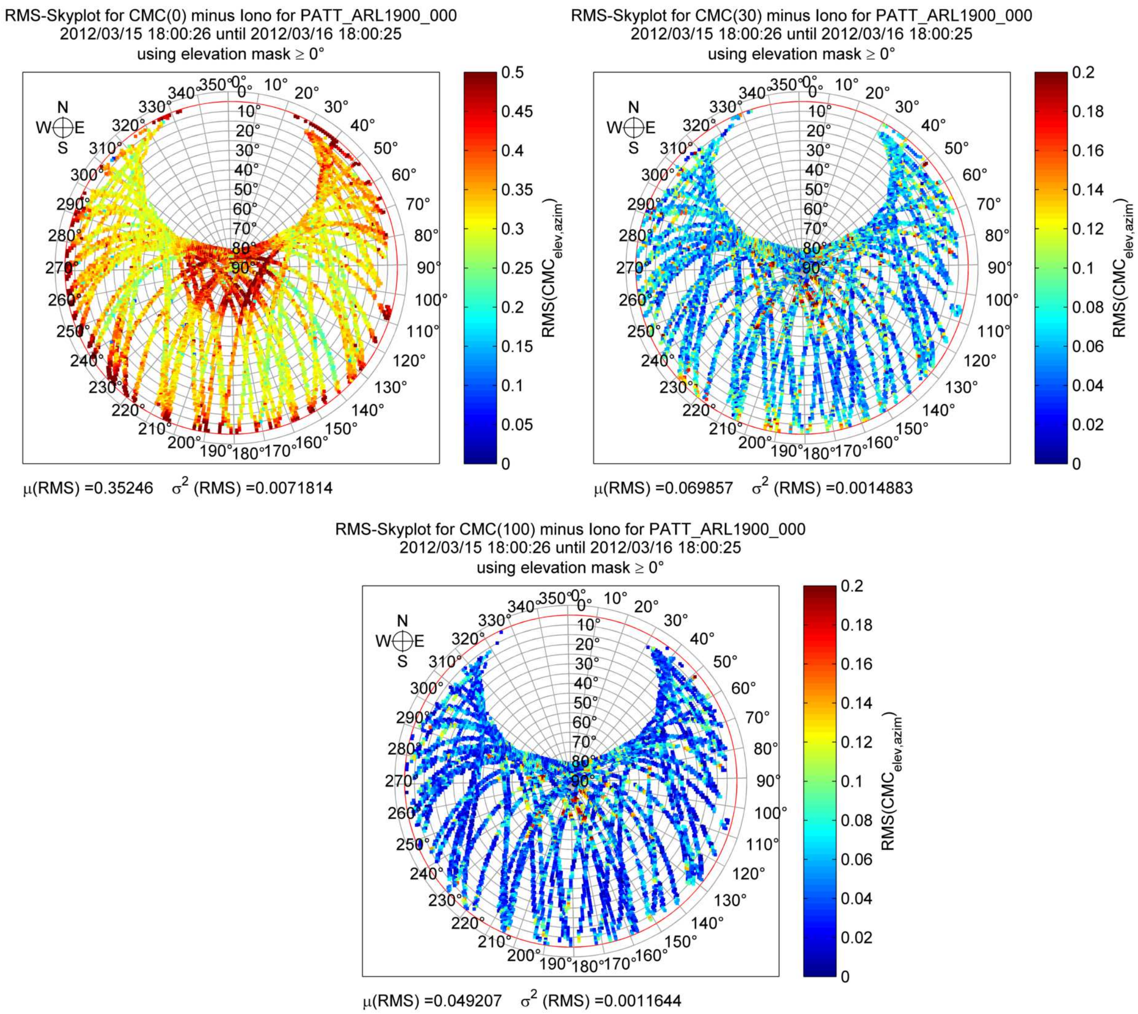


Figure 5-8: Examples of CMC skyplots for different smoothing time constants (from left: 0s, 30s, 100s) – Measurements from a single day, and a single antenna, with variation of smoothing time constant.

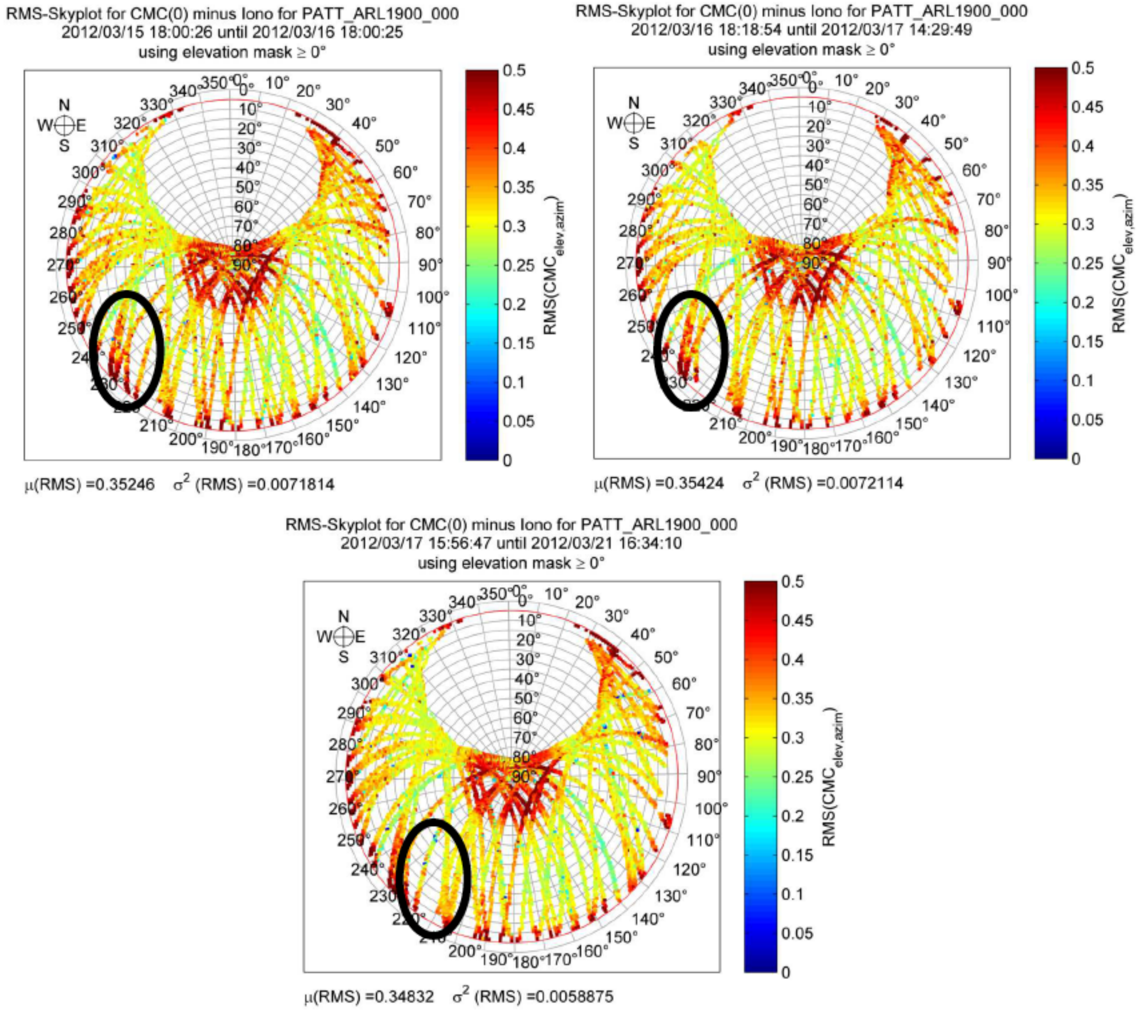


Figure 5-9: Example for reflector, whose influence will be reduced by smoothing.- Same antenna as before, now unsmoothed CMC result, shown over various consecutive days

- In order to assess the degree of correlated multipath a correlation analysis should be performed. The example included here considers the inter-antenna correlations between two antennas. Methodologies to consider correlations for a complete installation with four antenna may be defined by the manufacturer. The example plot in Figure 5-10 depicts histograms of the inter-antenna correlations obtained from measurement data subsets for different smoothing time constants (0s, 30s, 100s). These histograms are based on statistically independent samples. It can be seen, that the code-carrier smoothing increases the correlation between the antennas. The code-carrier smoothing reduces the noise and the ground reflection with its longer time constants is more pronounced, thus the correlation increases. It should be mentioned, that the correlation analysis can also make use of a skyplot depiction of the correlations. This helps in identifying directions of correlated multipath if they should be evident.

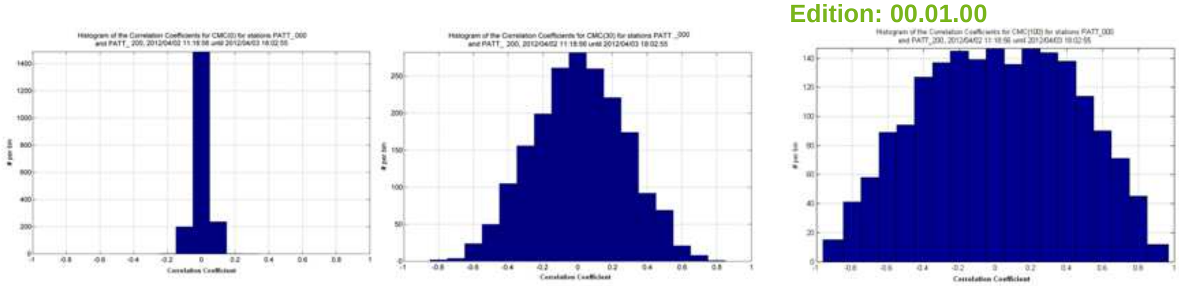


Figure 5-10: Example of histograms for inter-antenna correlations for different smoothing time constants (0s; 30s; 100s).

- Furthermore plots of the probability density function of the CMC values or Quantile-Quantile (QQ)[7] plot helps in the identification of overbounding needs and the identification of processing problems. Care must be taken to consider the effect of a sites elevation angle distributions, when assessing probability density functions over the entire data set.

5.3.4 Multipath evaluation tools

One of the tools available for evaluation of multipath, is the PEGASUS tool. It provides a dedicated multipath module (MP-module). To the knowledge of the author this is the only tool commonly available today. It provides single and dual frequency processing, however, it does not (yet) support merging of dual frequency data from one receiver with CMC data from another one. However, manufacturers and ANSPs usually possess their own proprietary tools, but they are typically not commonly available.

5.4 Obstacles preventing LOS (buildings, mountains,……)

Normally, VDB coverage of a specific area requires line-of-sight. Small obstacles like cars, masts and shelters are unlikely to cause coverage issues, whereas larger objects such as medium to large aircraft may cause such issues. Reflections and refraction may provide signal reception also at some distance behind larger objects.

For small airports with a single runway, it will normally be possible to find GBAS locations with line-of-sight to the entire coverage area. Refer to section 4.3 for a definition of the coverage area. There are some cases, however, where hills/mountains to the sides of the approach will shadow so that it is not possible to have line-of-sight out to ±10º to the sides of the approach. However, in these cases, it would be similarly difficult to meet the coverage requirements for ILS, and it is common practice to approve ILS's for operation with exceptions from coverage requirements where the signal is not operationally required. Figure 5-11 shows such an example, where the mountain to the north of the eastbound approach cases shadowing in the coverage area.

[7] The QQ-plot allows the assessment whether a measured distribution follows a modeled distribution. More generally, the QQ-plot is a graphical comparison of two distributions. It is based on plotting the quantiles of the first distribution, against the quantiles of the second distribution. The first distribution is represented by the condition y=x, such that it shows up in the plot as an increasing 45°-line. If both distributions are similar, the points from the second dataset lay very close to the line representing the first distribution.

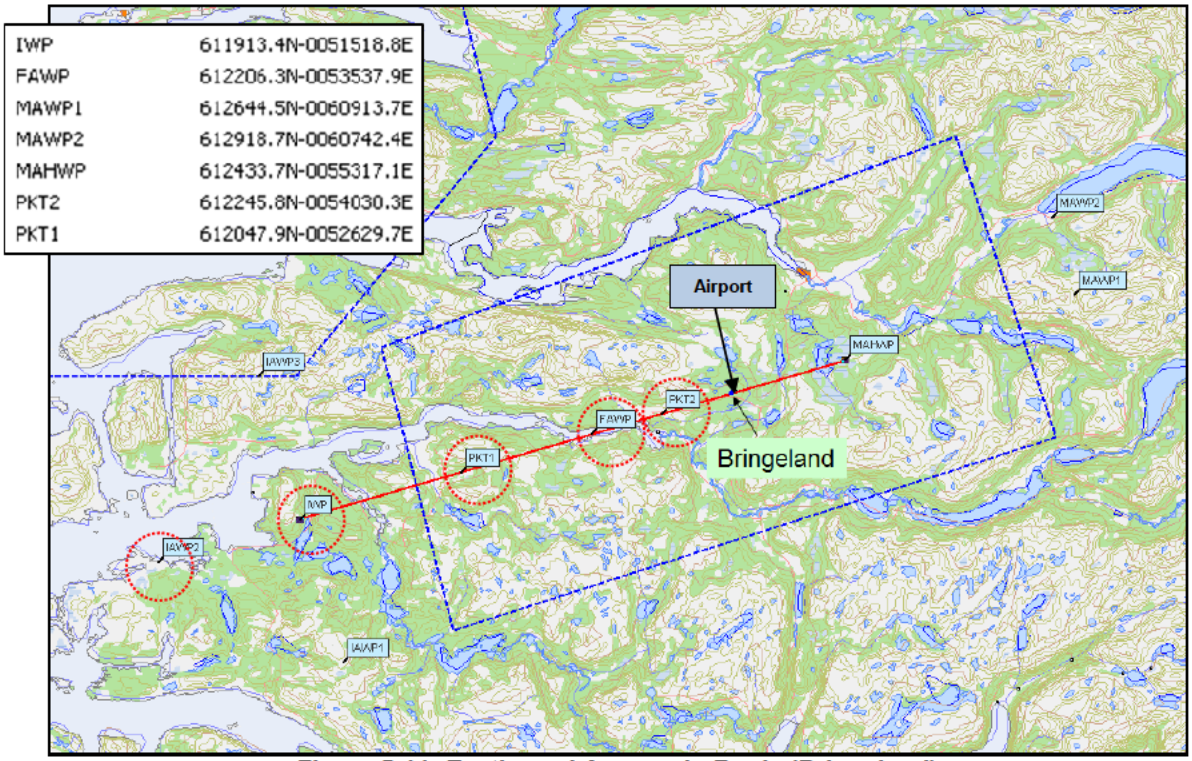


Figure 5-11: Eastbound Approach, Førde (Bringeland)

Figure 5-12 shows a different example, where installation of ILS is infeasible and installation of a GBAS covering the approaches could significantly improve safety. However, the terrain prevents a GBAS station being installed on the airport, as there would not be line-of-sight to the approaches. A station would have to be installed on the small mountain to the northwest of the airport to gain line-of-sight. None of these airports are candidates for CAT III, but on the approach, the coverage requirements are the same for CAT I and CAT III, making these airports relevant examples.

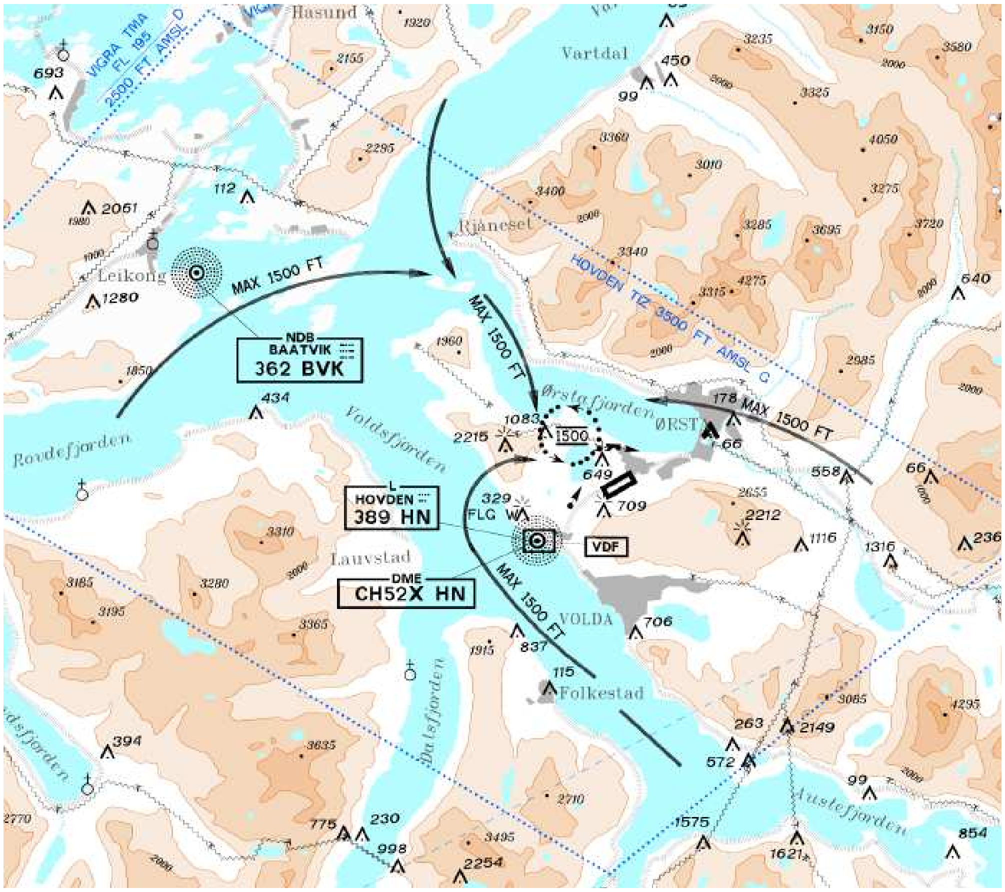


Figure 5-12: Ørsta-Volda/Hovden Airport

Although problems with line-of-sight to the coverage area on and to the sides of the approach can be challenging some places, there will normally be precedence for exceptions based on ILS practice. Coverage in the outskirts of the coverage area (e.g. ±35° at 28 NM) can be obstructed by mountains, but in this case, exceptions may be allowed since this is not an operationally relevant volume in this case. Coverage on the runway for rollout will be a greater challenge, and more relevant since CAT III airports can be large and complex with high traffic, all of which contributes to making coverage more difficult.

Again, Munich is used as an example. As was seen in Figure 5-1, there appears to be no locations on the ground within the 5 km circles that have line-of-sight to all runway surfaces. Possible VDB locations in this case could be the top of one of the central buildings, or to the west of the north and south runways, if it is possible to get far enough from the runways to have line of sight to both.

Simulations and measurements related to VDB ground coverage have been conducted by DFS, and are presented in [30]. Some simulation results are repeated here for convenience. Please refer to the paper for details of the simulations and tests.

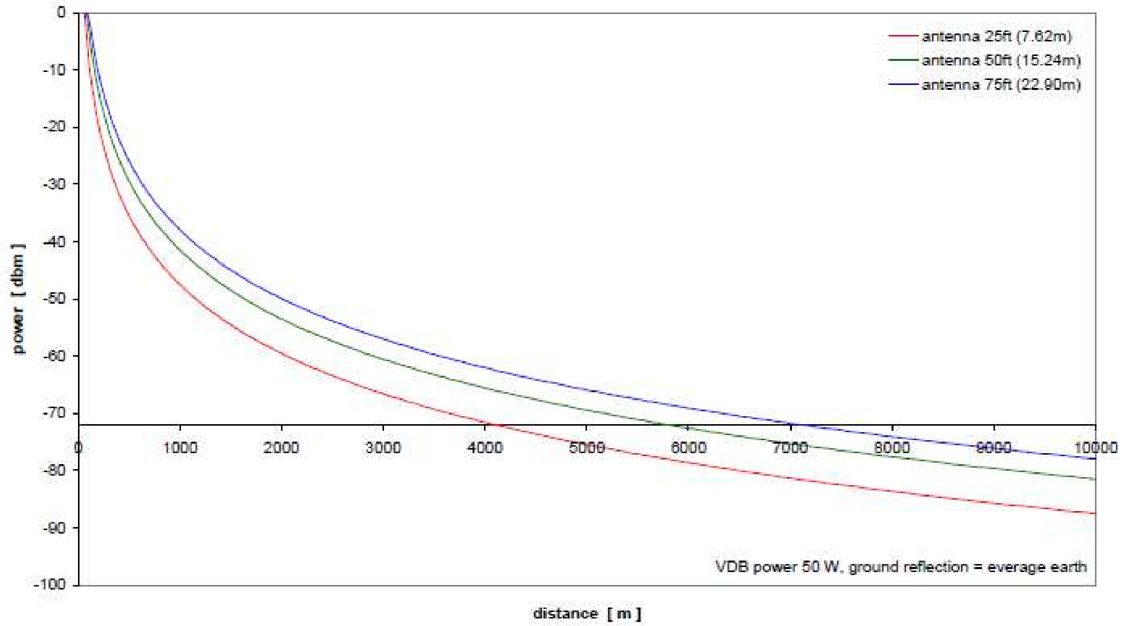


Figure 5-13: VDB Simulation results at 8ft (2.4m)

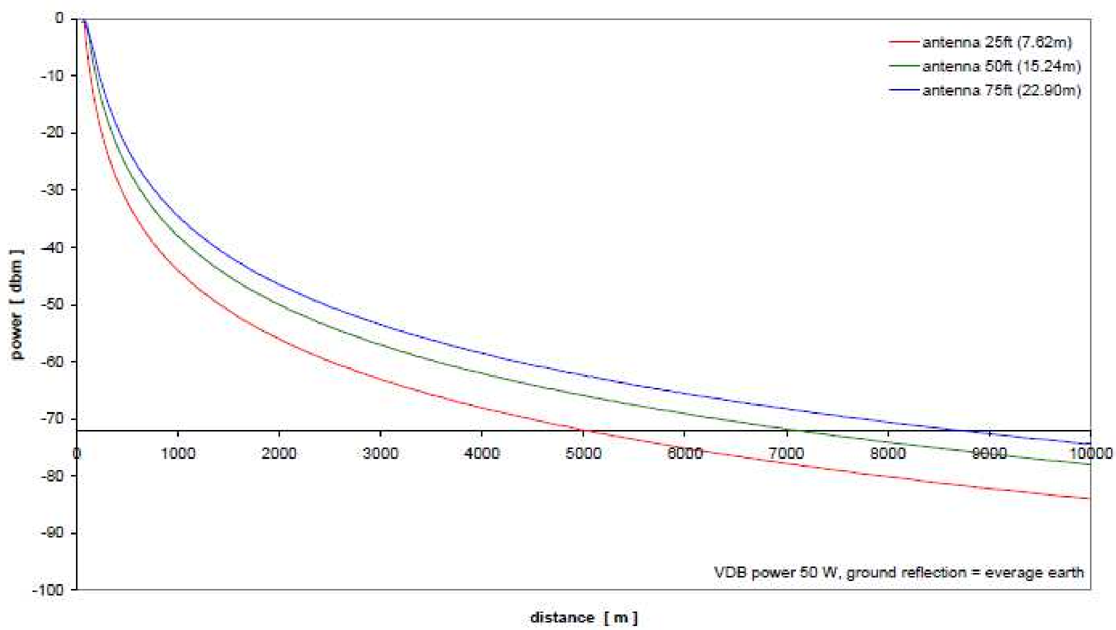


Figure 5-14: VDB Simulation results at 12 ft (3.7m)

As can be seen from the simulation results above, increasing antenna height provides better ground coverage. This is consistent with the antenna diagrams presented in Figure 5-15 and Figure 5-16, showing example antenna diagrams for horizontally polarised signals with increasing height. It can be seen from the figures that increasing height “presses” the first lobe towards the ground, increasing the field strength for low elevations. But is has the disadvantage that lobing may occur when the height above the ground increases.

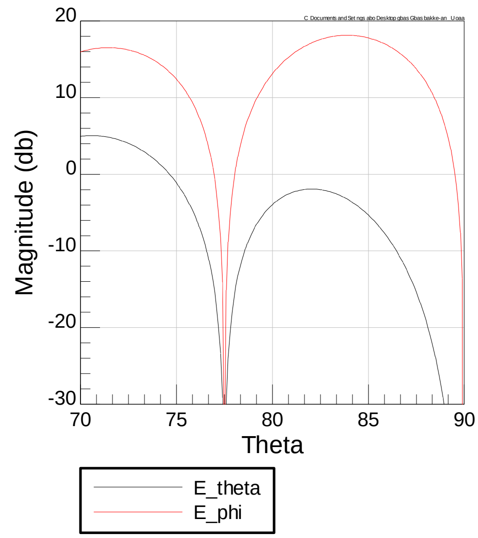


Figure 5-15: Radiation Pattern with phase centre 2 λ (5-6m) over ground plane

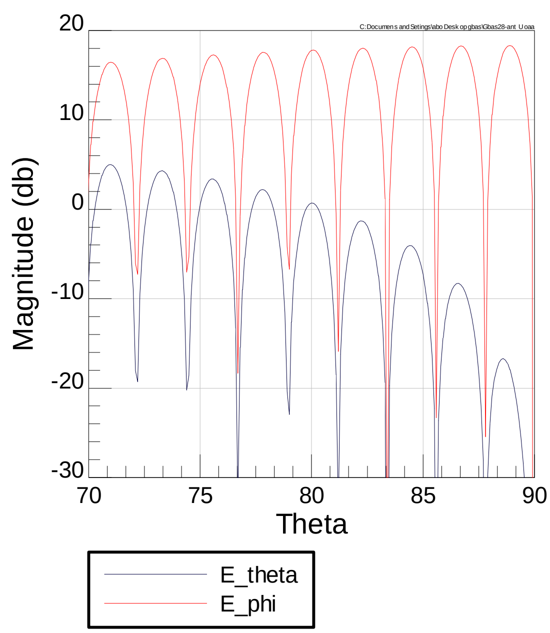


Figure 5-16: Radiation Pattern with phase centre 12 λ (28-34m) over ground plane

Some variations of antenna pattern may occur with antenna type, however, the behaviour of the diagram with respect to height over the ground plane is mainly due to the horizontal polarization of the signal. For the “rooftop installation”, (Figure 5-16), it can be seen that the first null is slightly below 3 degrees, where the field strength should be at its maximum. However, for a practical installation this could appear quite differently, since the environment is complex and reflections will tend to fill the fade holes. Therefore, if antenna heights of more than 2 λ is planned, such as for instance a rooftop installation is planned, detailed simulations must be carried out. However, a rooftop installation is rarely ideal for the GNSS antennas due to issues related to space, multipath and shadowing.

Therefore, installing the VDB antenna on a rooftop will normally require that the GNSS part and the VDB part of the ground station are physically separated.

Another possibility is to locate the VDB transmitter to the east of the airport, at a spot where there can be line-of-sight to all thresholds. Figure 5-17below attempt to identify a spot which has line-of-sight to both the south and the north runway.

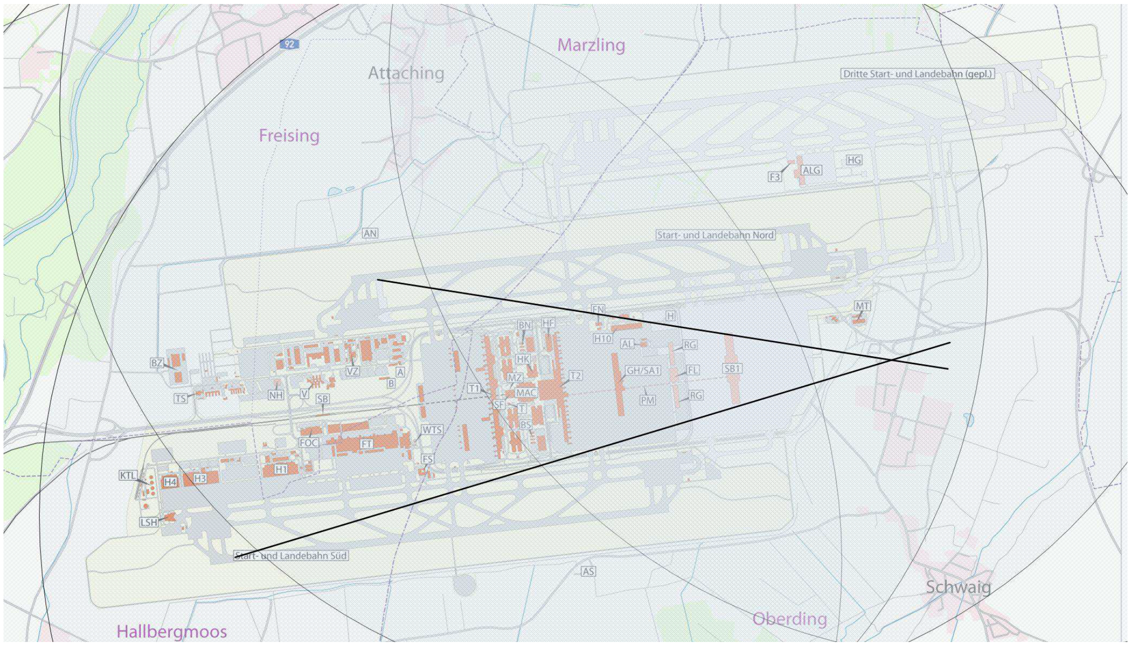


Figure 5-17: Line-of-Sight at Munich Airport

It can be seen that the only location which has line-of-sight to all runways are outside the airport perimeter. This is therefore not a very practical site for the VDB transmitter. Also, the line-of-sight to all runways from this spot passes through taxiways, which will cause shadowing. SESAR 15.3.6 T16 document "Early VDB Measurements at Frankfurt Airport" [19] investigates VDB coverage on the airport in general, and also looks at the impact of taxiing aircraft. Although also medium-sized aircraft like a Boeing B777 has an impact on the signal, the impact becomes more significant for large aircraft like Boeing B747 or Airbus A380. Reductions in signal strength in excess of 20 dB can be seen. However, since the signal strength on the airport is generally good due to limited free space loss, it is not given that this reduction in signal strength will cause loss of messages. This should be investigated further.

Due to the line-of-sight challenges, it is unlikely that a single VDB transmitter at Munich Airport can provide ground coverage to all runways, unless a rooftop installation can be used. A rooftop installation may however, as indicated above, have more problems on the approaches due to fade holes. One possibility could be a combination of a rooftop antenna to cover the runways, and a ground mounted antenna to the east of the runways, or to the west of the north runway to cover the approaches. However, for large, complex airports like Munich, it may be the case that not all runways are CAT III runways, and not all runways may necessarily require GBAS coverage, as some runways may be serving ILS-equipped aircraft only. In that case, siting will become easier.

Based on the above example, the following architectural measures that may mitigate the challenges addressed have been derived:

- Implementing architectures which allow the VDB part and the GNSS part to be sited independently (using e.g. fibre optic data cables to one or both of those two architectural components)
- Implementing architectures which allow more than one VDB transmitter to send on the same frequency in order to fill fade holes or blind spots.

- Implement alternative ionospheric monitoring schemes such as the IFM, in order to alleviate the 5 km baseline restriction.

Since airport layout, size and available space vary greatly from airport to airport, architectural measures like these may only be necessary on a limited number of airports.

5.5 Weather conditions (icing, strong wind)

The GPS antenna should not be covered by a huge amount of snow or ice, as this will reduce the received signal strength, and change the properties of the antenna. The effect of this is mainly reduced availability, but continuity can also be affected due to more frequent signal losses.

Generally, the design of the antennas is important for avoiding build-up of snow and ice. Horizontal surfaces should be avoided, and the antenna radomes should be cleaned and polished before the winter. This helps water and snow to run off more easily, in order to avoid build-up and icing. When snow or ice build-up on the antennas cannot be avoided, a procedure must be established for snow removal. Generally, icing on antennas is a continuity issue since it reduces the power level and at some point will trigger power monitors. The specification in ED-114 [1] is to operate with 50 mm of ice coating. Tests performed with the Aeroantenna AT-595 show that this thickness of solid ice coating does not cause any problems. What do cause problems though, are similar amounts of wet snow/water. This caused marginal signal levels and occasional outages. Practical experience from SCAT-I, with approximately 15 ground station/winters on the coast of Norway, on latitudes between 65 and 71 degrees, have not revealed any problems in operation due to snow or icing. These radomes do not provide an active de-icing function, however periodic cleaning and polishing have been carried out.

The prevailing snow conditions on the site should be taken into account during installation. In areas where snow is common, the antenna mast height can be adapted during installation in order to avoid having to remove snow during winter. Mounting the GNSS antenna on a mast may also be relevant for other reasons, such as RFI, see section 4.2.

However, lengthening the antenna masts in order to take into account the snow conditions or RFI, has the disadvantage that the antenna will be more prone to vibrations during high winds. The wind specification in ED-114 [1] is that the station shall operate up to 36 m/s (130 km/h, 70 kts). Under these conditions, the antennas may suffer from vibrations, especially if they are mounted on masts. Vibrations may cause loss of lock, or it may cause noise-like disturbances on the signal.

Figure 5-18: Winter conditions

Generally, the amplitude of vibrations should be less than 3 cm. However, it depends on the monitoring scheme whether this amplitude of vibrations will be acceptable for GAST D. For instance, if the Absolute Slant Ionospheric Gradient Monitor based on carrier phase double differences is used, millimetre amplitudes may be required. This needs to be further investigated. If this is the case, it is assumed that some wire/rope-based mounting reinforcement will be needed for reliable operation under all weather conditions.

Weather conditions may also affect the multipath conditions. In general, wet weather, or wet conditions followed by frost increases multipath. When performing site qualification, the surroundings (within the outer LOCA) should be considered with respect to whether there are any possibilities for water build-up. If it is not possible to avoid areas with ponds, sea view, moor or flooding, these aspects need to be taken into account. Reflections that are likely to occur from these areas should be masked out. Also, if possible, data from periods of wet conditions should be analysed for changes in multipath behaviour in order to ensure that σ_{pr_gnd} will bound the error under all weather conditions.

In addition, compact snow, wet snow and ice on the ground may impact the multipath conditions. Attempts have been made to derive some correlation, but this is difficult to do since the multipath conditions are generally related to the property of the surface, which is not an observable available from meteorological observations. Assumptions about the properties of the surface have to be made based on precipitation, minimum and maximum temperatures prior to the time in question. There are indications that wet snow and snow with an ice cover on increases the multipath, but the errors are limited. The maximum error observed over a 4 km baseline is 1.6 meter over a two month period during winter, and the XPL bounded the error at all times. However, it should be noted that changes done to the ground in order to reduce multipath, such as adding gravel, will have limited effect since σ_{pr_gnd} shall bound the error at all times under all conditions, also when the gravel is covered with wet snow or ice.

As it has been stated above, weather conditions like wet terrain, frost or snow on the surfaces around the antennas increases multipath. Weather conditions affecting the RRA, increases multipath on GNSS signal, which should be bounded by σ_{pr_gnd} and might degrade the performance of GBAS station. Weather conditions affecting the VDB antenna, increases multipath on VDB signal, which might affect the coverage area. Effects on RRA are more significant and as far as possible should be mitigated, i.e. terrain environment around RRA should mitigate weather conditions. As an example, figure below shows the mitigations applied in Malaga GBAS station to reduce the effect of wet terrain around RRA (by covering the surface around the RRA with gravel) and the effect of flooding around antennas (by building drainage capable of evacuating heavy rain and levelling out the terrain).

Figure 5-19: Antennas landscape (GBAS Cat-I in Malaga).

5.6 Security

It is possible to foresee three different types of threats against GBAS operations:

- Physical intrusion
- Electronic Intrusion
- RF Interference

Each of these threats will be assessed in detail in 15.3.6 Task 22 Safety and Security Risk Assessment. However, in order to identify any impact these aspects may have on siting and installation, they are briefly addressed here.

A security assessment is a process similar to a safety assessment in that it studies the impact of possible event on the safety requirements of the system, but it differs from the safety assessment in that the “events” in question are deliberate actions of personnel, rather than arbitrary faults of equipment. Some methodologies and examples of security assessments are available, see for instance the FAA/EUROCONTROL COCR Report that performs a security assessment in an ATM related environment [20]. In addition, work is ongoing within SESAR in order to develop and evaluate methodologies for security assessment.

Security threats may be executed for several reasons. There may be individuals or organisations which have the intention to cause accidents. These actions may be carefully planned, and the people involved may have significant resources and a strong motivation to carry out their intentions. Then there are groups or individuals who do not necessarily want to cause harm to other people, but intrudes/interferes to “show that they can”. These may not have the same level of resources, but may be highly motivated and skilled. Then there are those who wilfully cause risk to air traffic, without necessarily fully understanding the risk they impose (e.g. exposing pilot to laser emitters during approach). In any case, the possible risks need to be understood in order to put adequate protections in place. The protections are partly in the construction/architecture of the equipment, and partly in the physical and electronic barriers surrounding it.

It should be noted that it is common in security assessments to assume that personnel are loyal to the level of clearance they have. Thus, given that the organisation has a security arrangement that implies that only a limited group of personnel with the necessary trust and training, have access (physically or electronically) to sites/equipment, it can be assumed that own personnel does not impose a security threat. However, this assumption should be further discussed within the scope of 15.3.6 Task 22.

Any wilful action, which may cause a violation of the integrity or continuity of a GBAS ground station, is a security threat. Although the integrity and continuity requirements themselves may be complex and difficult to understand (refer for instance to SESAR 15.3.6. deliverable D03 [6]), it is relatively easy to identify whether a specific action can have the potential to violate any of these requirements.

Security Assessment methods such as the one used in the COCR Report [20] focuses on the following threats:

- Denial of Service
- Altering of information
- Information leakage

Information leakage is rarely a significant issue within ATM security. Un-encrypted RF data links are in widespread use, based on public standards and protocols. Protection of information therefore has limited effect from a security point of view.

Denial of service-attacks may potentially cause loss of continuity, e.g. if attacking the GBAS signal or the VDB link. Altering of information may cause loss of integrity. All interfaces will have to be assessed with respect to possibilities for these types of attacks.

5.6.1 Physical Intrusion

This threat includes cases where unauthorised personnel gains access to the GBAS installation or parts of it. The table below briefly addresses the threats and consequences.

Action	GBAS Element	Safety impact	Remark
Move	GNSS part	Integrity	This is a highly unlikely threat as all antennas must be moved synchronously in order for it not to be detected. However, it is essential that GNSS antennas are physically protected by placing them inside the airport security fences.
Damage/disconnect	GNSS part	Continuity	This is relatively easy to do, and therefore, the GNSS antennas must be located inside the airport security fences.
Move	VDB part	Continuity	VDB part to be sited inside security fences.
Damage/disconnect	VDB part	Continuity	VDB part to be sited inside security fences.
Intrude	Shelter (local MDT and/or rack)	N/A	These risks are addressed under electronic intrusion

5.6.2 Electronic Intrusion

This section addresses intrusion on electrical interfaces except the RF-interfaces (GNSS signal and VDB signal). This section assumes an architecture corresponding to the one standardised in ED-114 [1] with respect to which interfaces are in place. An intrusion like this can be carried out by physically intruding in the shelter and then access one of the interfaces available, or by accessing interfaces available elsewhere on the airport or outside the airport.

Action	GBAS Element/ interface	Safety impact	Remark
Denial of service	MDT interface	Availability	A denial of service attack against the MDT interface will have no effect on integrity or continuity since the MDT is not required for normal operation of the equipment. A necessary assumption for this to be true is that the architecture of the ground subsystem is such that the ground station itself is protected against any sort of malfunction of /attack against the MDT[1)]. Depending on the local concept of operation, the operator may chose to remove the GBAS from service until the situation is resolved.
Alter	MDT Interface	Integrity	If a person is able to intrude through all barriers related to the MDT interface, it will be possible to alter integrity critical data. This is one of the most critical interfaces and functions in the GBAS, therefore sufficient measures must be taken to protect it against intrusion. Suggestions to be considered are: - Not to allow this interface outside the shelter - Physical protection of the shelter - Password protection of the interface - Physical disconnection of the interface during operation - Security log detailing all reconfiguration operations preformed - Additional tools needed to change integrity related data (e.g. FAT data) are not available at the ground station site
Alter	MDT Interface	Continuity	It may also be possible to alter continuity critical data over the MDT interface, and to turn the VDB transmission on and off. This is not as critical as altering integrity related data, and it could therefore be considered to separate functions related to integrity and continuity on different interfaces in order to allow a lower security level for continuity related functions. E.g. it may then be possible to allow continuity related operations from outside the shelter, whereas integrity related operations may be prohibited.
Denial of service	ACSU/RCSU interface	Continuity/ Availability	The RCP/ATC interface will normally not carry data which can have impact on the integrity. Any non-standard implementations which have this needs to take it into account in their safety/security assessments. Denial of service of this interface may affect continuity, depending on the design of the ground station. It is recommended that the ground station is

			designed to continue operation when loss of contact with the RCP and ATC interfaces. In that case, a Denial-of-service attack against this interface will cause loss of availability as the ATC personnel may terminate GBAS operations when there is no contact with the ground station.
Alter	ACSU/RCSU interface	Continuity	This interface could carries continuity critical data such as VDB on/off commands, reset commands etc. For this reason, the interface should be protected. Normally, this interface is physically protected since there is a dedicated copper cable from the shelter to the equipment room/tower. If this interface is combined with other functions or extended outside the physically protected area, additional protection is likely to be required.
Denial of Service/Alter	Power	Continuity	Changes to/removal of power may/will cause loss of continuity. Power supply therefore needs to be physically protected (and potentially doubled).
Alter	Antenna cables/connections	Integrity	There could be several ways to violate integrity requirements by disconnecting antenna cables and inserting a false signal on the input, e.g. using GNSS signal generators. However, the swapping of cables must happen within the alarm limits in order to avoid an alarm being set, and the signal must be credible. Inserting a false signal on the VDB interface will cause the monitor to trigger (however, the false signal will still be transmitted. Physical protection is needed. It could also be considered whether disconnection of GNSS antenna cables shall require a restart of the ground station.
Denial of Service	Antenna cables/connections	Continuity	Removal of antenna cables will cause loss of continuity. They therefore must be physically protected.
Denial of service/alter	Data logging port	No safety effect	A pre-assumption for the conclusion that attacks on the data logging port has no safety effect, is that the data logging port is sufficiently partitioned from the ground station (preferably by hardware)[1)]

1) It is assumed that the MDT and the data logging port are sufficiently partitioned from the operational parts of the ground station so that an attack on these interfaces cannot impact the operation of the ground station. In theory, this can be done either by hardware- or software partitioning. Generally, hardware partitioning is less flexible since it requires physical presence to remove the barrier (such as turning a switch, connecting a cable etc). Software partitioning could be more flexible, but it could be difficult to certify, as it can be difficult to convince the authorities that the security is sufficient. Software barriers may also require periodical updates to ensure sufficient security over time. This is impractical in a certified system.

5.6.3 RF Interference

The aspects of RF interference on the GNSS signal are addressed in details in section 5.2. Therefore, this subject is touched on only briefly here. Interference on the VDB signal is addressed here.

Action	GBAS Element/ interface	Safety impact	Remark
Denial of service	GNSS Signal	Continuity	This is typically what is referred to as jamming, which is addressed section 5.2. Typical mitigations are enforcement of regulations, larger separation between GNSS antennas, increasing antenna height, and implementing robust architectures.
Alter	GNSS Signal	Integrity	This is typically caused by repeaters, which are addressed section 5.2. Typical mitigations are enforcement of regulations, and ground monitoring mechanisms.
Denial of service	VDB Signal	Continuity	The VDB frequency band is a protected band and jamming has traditionally not been a significant problem in Europe. In other parts of the world however, the problems may be significant and some operators may require several VDB frequencies to be used. This will however not mitigate the risk to the continuity, since it will be necessary to re-tune the avionics receiver. Generally, enforcement of regulations is an adequate mitigation against this threat.
Alter	VDB signal	Integrity	A station sending false VDB signals will be a threat to the integrity of the operation. In order to mitigate this, the authentication protocol has been standardised, and is a mandatory requirement for GAST D. The authentication protocol ensures a strict mapping between selected approaches and the time slots in use, and the time slots are filled up in order to ensure that no false messages can be fitted into the allocated slots.

5.6.4 Summary of Siting Requirements Related to Security

The most important requirements derived from security aspects are:

- Avoid siting all GNSS antennas close to public areas
- The GNSS part, VDB part and the shelter must be sited in a secure area (inside airport security fence)
- Interfaces going out of the secure area, which carry integrity critical data, must be adequately secured or partitioned from the operational part of the system. Similar security measures should be considered for interfaces carrying continuity critical data.

5.7 Impacts of the ionosphere on siting

Within this section siting implications resulting from the coverage of the effects of anomalous ionospheric conditions will be discussed.

Siting restrictions resulting from the mitigation of the effects due anomalous ionospheric conditions were already defined for GAST C in context of the scheme to cover the threat for GAST C. However, since GAST C is out of scope here, the focus will be laid purely to the needs for GAST D.

With GBAS GAST D the mitigation of the threat for anomalous ionospheric conditions is shared between the airborne and the ground subsystem. As a consequence of this shared responsibility the ground subsystem has to monitor spatial and temporal ionospheric delay gradients, not visible/not detectable to the approaching airplane.

First, the ionospheric threat will be described. Since there is a dependency of the threat space on the geographic region, this impact will be discussed to the extent currently known. Together with the threat space the need for ground detection of spatial ionospheric gradients will be introduced. Following this, the currently discussed detection schemes for the ground subsystem will be given and the resulting siting influences discussed.

Siting restrictions due ionospheric anomalies result from the need to detect a certain minimum spatial gradient, but also from the maximum gradient which has to be considered. The favored monitoring scheme is based on carrier phase double differences and has distinct detectable ranges. These detectability bands result from the carrier phase ambiguities.

This leads to the need to consider this maximum gradient too. The resulting influence on the siting process and installation needs will result from:

- projection of detectable range to the runway directions
- depending on applicable threat space and used antenna / receiver technology: several baselines might be necessary
- certain phase centre stability to be assured

These drawbacks of the proposed detection scheme led to initial investigations performed by Thales on the applicability of code based measurements. Such a scheme would be based on separate, additional ("Far Field") antennas and requires relatively large separations (~20 km). Thus the possibilities of such processing are relatively limited.

Until further monitoring or mitigation schemes are published and commonly accepted, the carrier-phase double difference methodology will be considered solely (could be adapted if further common knowledge is recognized/discovered).

The following descriptions are based on Thales' performance evaluations performed for GAST D in P15.3.6 task T07 and are given in the document D07 [56]. For convenience a summarized and adapted representation will be given here.

5.7.1 Threat-model and location dependency

The geographic dependency of ionospheric activities is outlined in [57]. With respect to absolute ionospheric delays three geographic regions were introduced:

1. the low-latitude regions including the equatorial and equatorial "anomaly" regions (shown as one band between 20º N and 20º S of magnetic latitudes in Figure 5-20),
2. the mid-latitude regions (extending from 20º to about 65º), and
3. the high-latitude regions (above 65º) which include the auroral and polar cap regions.

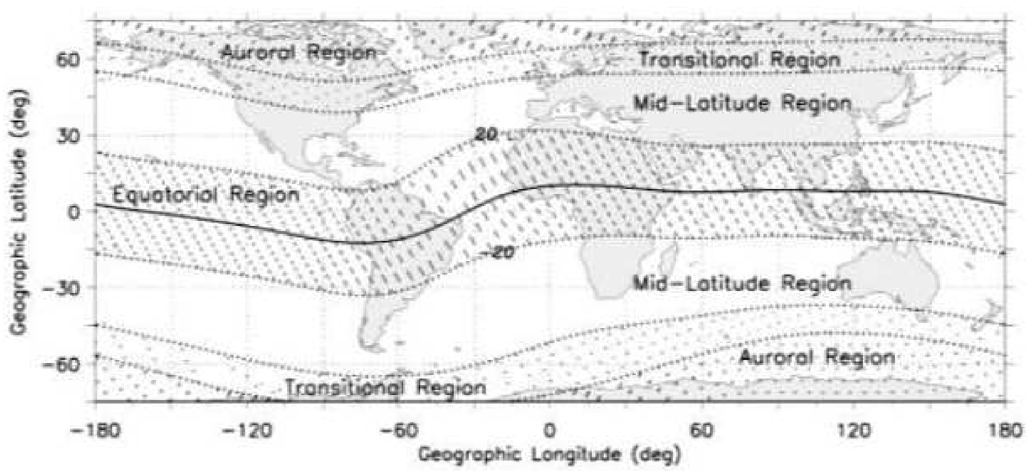


Figure 5-20: Ionospheric Region [57]

Due to GBAS' differential corrections not the absolute ionospheric error is of concern, but the residual, ionospheric decorrelations between the ground subsystem and the aircraft. While the nominal

ionospheric decorrelation for GBAS is covered by the protection level concept, conditions exist, which lead to rapid or small scale changes in the local ionosphere and thus lead to differences in the ionospheric delay seen by the ground subsystem and the aircraft.
Even if the regions characterizing the ionospheric activity refer to ionospheric activity in general, they also apply for GBAS.

The basic GBAS threat model for ionospheric gradients, underlying the GBAS GAST D SARPs ([8]) is described in NSP09/WP29 [58].

The CONUS threat model is a simplified characterization of ionospheric gradients, characterizing these gradients by the three parameters front width, W, front speed, v and gradient, g.
The derived threat space is based on GPS single and dual frequency measurements over the last solar cycle. The threat space is described by equations E1 and E2 with elevation and ground speed dependent bounds. This threat space reflects the worst-case ionospheric fronts observed during the last solar peak (~2003). It should be noted that the constraint on gradient g restricts the maximum "height" of a front, representing the maximum residual ionospheric delay, to 50 meters (slant delay on L1 carrier frequency). This threat model and threat space has been accepted by the FAA and has already been used as basis for the GAST C certifications.

$$TM_{CONUS}(g, v, W) \begin{cases} g < min\,[50m/W, g_{max,CONUS}(\theta)] \\ v < 750m/s \\ 25km < W < 200km \end{cases} \qquad \text{[E1]}$$

$$g_{max,CONUS}(\theta) = \begin{cases} 375ppm, 5° < \theta \le 15° \\ (360+\theta)ppm, 15° < \theta \le 65° \\ 425ppm, 55° < \theta \le 90° \end{cases} \qquad \text{[E2]}$$

For the demonstration of GAST D feasibility a conservative rendition of the original CONUS model as given in [58] is applicable.

Propagation Speed (v)	Upper Bound on Gradient Slope (g)
v < 750 m/s	500 mm/km
750 ≤ v < 1500 m/s	100 mm/km

Table 4: Parameters of the CONUS ionospheric wedge model

It should be noted, that the model does not assume any a priori probability for an anomalous ionosphere. However, in order to derive reasonable results, reflecting the anomalous nature of these large ionospheric gradient, a priori probability of 10^{-5} as proposed in [59] should be assumed. Thales also investigated the impact on the monitoring scheme when a priori probability of 1 would have to be assumed [56].

However, in order to be conservative for ionospherically more active regions an upper bound on the gradient range was proposed to be set to 2000 mm/km [59] and to assume this increased maximum gradient for the development of the absolute gradient monitor. Therefore, even if this extension is not a requirement, Thales has investigated the influence of this extended upper bound in order to provide better evidence on the GAST D feasibility. Recent investigations performed in geographic regions with higher ionospheric activity indicate that the assumption of higher ionospheric gradients is reasonable [61]. It should be noted, that with the raised upper bound on the gradient, the constraint on the maximum additional delay was not changed. With this, only one gradient / front width combination is possible for the maximum gradient of 2000 mm/km, namely the one for the minimum front width of 25 km. For every other combination, a gradient of 2000 mm/km would harm the threat model.

Worldwide several activities are ongoing to determine the local ionospheric threat space for GBAS.

For Germany, the DFS initiated the development of a German threat space. The result of this research is described in Ionospheric Threat Model Validation in Germany (DFS), [60]. As a result lower maximum ionospheric gradients over Germany were found. In consequence the German threat space puts lower bounds on the on the maximum gradient compared to the CONUS threat model. This model is characterized by the following parameters:

$$TM_{DLR}(g,v,W)\begin{cases} g < min\left[50m/W, g_{max,DLR}(\theta)\right] \\ v < 1200m/s \\ 25km < W < 200km \end{cases} \quad \text{[E5.3]}$$

$$g_{max,DLR}(\theta) = \begin{cases} 40ppm, 5^\circ < \theta \leq 30^\circ \\ \left[40 + 2.5\cdot(\theta-30)\right]ppm, 30^\circ < \theta \leq 70^\circ \\ 140ppm, 70^\circ < \theta \leq 90^\circ \end{cases} \quad \text{[E5.4]}$$

In the frame of Spanish GBAS activities the assessment of the ionospheric threat space for Spain was performed [62]. According to information received from AENA this study is finished. The scope of the activities was to validate the applicability of the CONUS model to the Spanish mainland. It was not intended to propose an “adapted” iono threat model. The validity of the CONUS threat space was confirmed. None of the ionospheric gradients measured represent an integrity risk for the GBAS station (all gradients observed were properly covered by the SLS-4000 geometry screening algorithms and integrity monitors).

The ionospheric behavior was analyzed over Spain (except for the Canary Islands) during the last solar cycle focusing on the solar maximum activity which occurred between 2000 and 2003. The analysis showed several cases of high ionospheric activity with medium gradients (the largest ones smaller than 300 mm/km). For those periods with larger gradients, the same behavior of the ionosphere was found, which is characteristic of the ionospheric storms; this behavior is similar to ionospheric equatorial anomaly (IEA), but after its study and considering the Iberian Peninsula is located in geomagnetic mid-latitude and the IEA occurs at low-latitude, it is attributed to ionospheric storms.

Ionospheric events were modeled as a linear front moving at constant speed (m/s) and characterized by its gradient (mm/km). This model was designed to represent ionospheric storms (e.g. CONUS, November 20th 2003), but it is also valid to represent IEA (Ionospheric Equatorial Anomaly). The final threat model included in the FAA Cat I certification did not include a front speed dimension. Instead, the front speed dimension was replaced by (observed) ranging source elevation angle.

The analysis performed in Spain was performed for GBAS CAT I. Even if with respect to GAST D differences in the siting implication will result, the underlying threat space for GAST D is principally consistent with the CONUS threat space. Siting differences result since in the GBAS CAT I scheme the maximum RWY distance shall ensure the limitation of the maximum ionospheric error in vertical direction, whereas in GAST D the correct detectability of gradients by the ground monitor is in focus.

Furthermore a Eurocontrol initiative is ongoing to develop the ionospheric threat model for the entire ECAC region. This development intends to cover the expected coming solar cycle, [72].

Widen the focus to worldwide activities it becomes obvious that Japan is very active to develop a threat model for equatorial region as described in [70] and [71]. The ionospheric threat model for GAST D is considers also the impact resulting from ionospheric bubbles, [73], .

However, with regard to European threat space, and especially with regard to the German bound on maximum ionospheric gradients the need for spatial ionospheric gradient monitoring could be of doubt.

In ([63]) it was shown, that for a five kilometer distance to the threshold, an ionospheric front with 300 mm/km can cause an undetected error in the order of 1.5 m at the aircraft. Considering anomalous ionospheric gradients as a malfunction to GBAS, the resulting pseudorange error has to be bound to 1.5 m (exact would be 1.6 m). Therefore, the 300 mm/km define the lower bound of the threat that has to be detected. Also, the maximum antenna distance to the threshold was set to five kilometers. As mentioned, the upper bound was set to 2000 mm/km. Depicted in Figure 5-21 it can be seen, that if the maximum separation would be exceeded, smaller gradients would have to be detected.

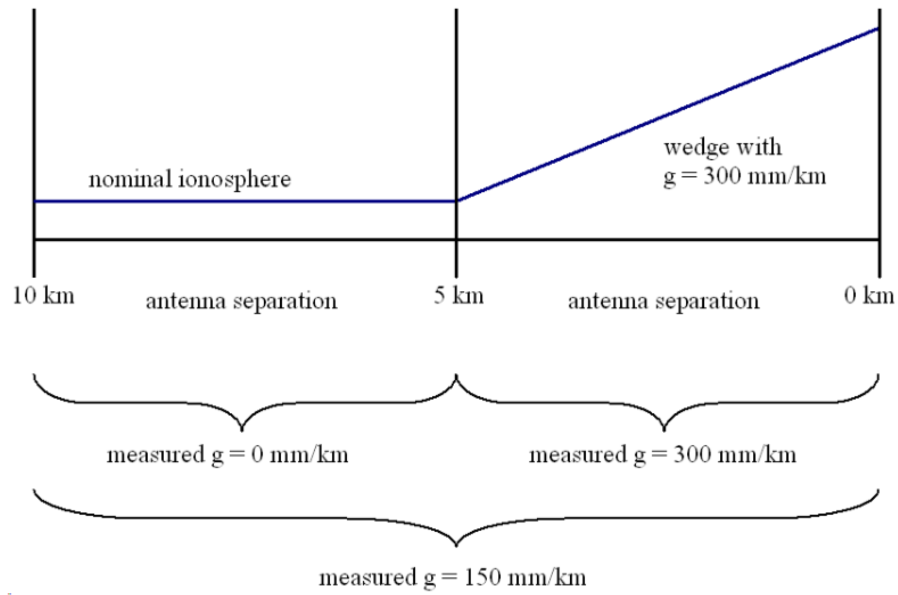


Figure 5-21: Potential problem for antennas which are separated more than five kilometers

5.7.2 Overview on the possible scheme to cover the ionospheric gradient threat for GAST D

While the nominal conditions are bounded by σ_{vig} → xPL => integrity level: $5 \cdot 10^{-8}$ in any 150 second approach interval, for precision approach CAT-III service, the irregular ionospheric conditions must be detected and mitigated. According to above stated the ground subsystem has to detect temporal and spatial ionospheric gradients. Typically two types of monitors exist to ensure proper detection: A temporal and an absolute monitor to cover all potential scenarios needed for which the GS has to provide protection. The second is mainly for the reason of detecting gradients that affect a satellite-receiver path already at acquisition, when a temporal monitor would not detect anything.

5.7.2.1.1 Temporal Gradient Monitoring: CCD

The ground temporal gradient monitoring can be done by the ground CCD monitor. The CCD monitor measures and calculates temporal gradients that are visible for the ground station.

5.7.2.1.2 Absolute Gradient Monitoring

A method to detect stationary spatial gradients that are only visible to the ground station and not for the airplane and which already exist at satellite acquisition was developed and published by Samer Khanafseh of the Illinois Institute of Technology (IIT) in ([59]) The basics and equations for the method can be found in that paper. In principle, the method uses L1 carrier phase measurements of two receivers to form double differences (DD). The benefit of DDs is that all common error terms cancel out and only differential error terms like differential orbit, multipath, noise and differential ionosphere (called ionospheric gradient) remain. Due to the potential carrier phase ambiguities which cannot be separated from ionospheric gradients and which are removed during building a test statistic, non-detectability regions result. These non-detection regions increase with increased noise of the monitors test metric. As has been discussed in [63] an increased maximum gradient detection needs may lead to the need to combine multiple baselines with different lengths in order to cover the whole threat space.

5.7.2.1.2.1 Using Code Measurements for the Absolute Ionospheric Gradient Monitor

In addition the carrier phase based absolute ionospheric gradient monitor can be varied slightly to use code measurements instead of phase measurements. Due to the significant increase in noise, filtering is needed. If gradients as low as 300 mm/km shall be detected by those methods, the required separations would become too long and thus the 5 kilometers constraint would be harmed. Therefore, those code based absolute ionospheric gradient monitors could only help to detect very large gradients. A code based monitor would provide the advantage to be able to detect indefinitely large gradients.

In order to cover the entire range of gradients to be detected with carrier based monitoring, relatively short baselines – smaller than 400 m – are required. Furthermore constraints resulting from redundancy need to be considered. Therefore code based means to cover very large gradients are seen to require additional (pure monitoring) antennas sited along the imaginary line from GBAS reference point along the approach path direction. For a first assessment of feasibility, Thales has used its initial performance results as described in [56] for the CMC(100) values for the combined noise performance of a GAD B and a GAD C antenna and the actual noise for such a code based absolute ionospheric gradient method was calculated with the help of error propagation.

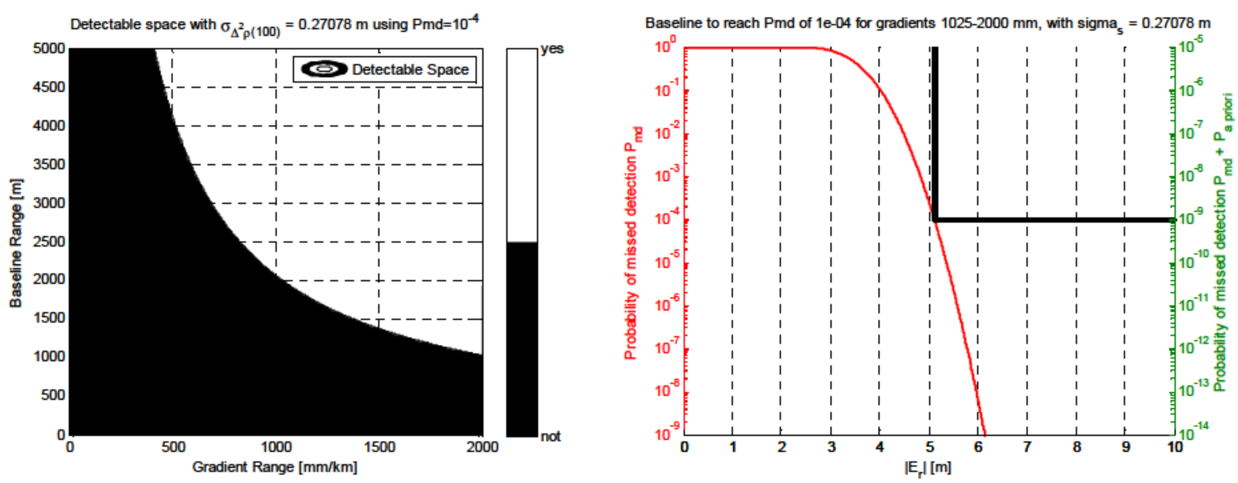


Figure 5-22: Detectable space for a code based absolute gradient monitor for $P_{md} = 10^{-4}$ (left) and resulting P_{md} for code based absolute ionospheric gradient methods assuming a detection need for gradients larger 1000 mm/km (right)

These initial results indicate, that it is possible to detect gradients starting with 1000 mm/km. The malfunction P_{md} of 10^{-4} ($P_{a\_priori} = 10^{-5}$) requirement would then be fulfilled with an antenna separation of 3000 m. Figure 5-22gives an example of the graphical representation.

The main siting restriction for GBAS GAST D ground subsystems is defined in the SARPS, and requires that the maximum distance from the GBAS reference point to any threshold used to support GAST D approaches is less than 5 km (see also Figure 5-21).

For the carrier phase based monitoring, the test metric noise influences the siting, due to a functional relation between the detection space, the test metric noise and baseline lengths. This relation is shown in Figure 5-23.

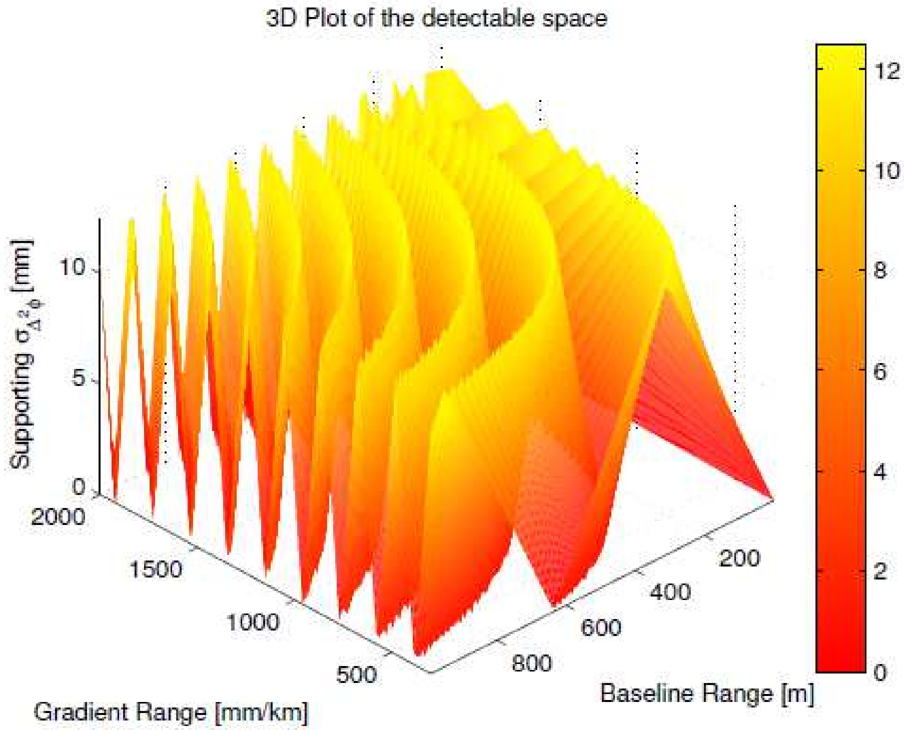


Figure 5-23: Detectable space for *c*arrier phase based ionospheric monitoring

It can be seen that with decreasing standard deviation test metric noise $\sigma_{\Delta^2\phi}$ the non-detection region decreases and thus more flexibility in choosing the baseline lengths is given. The largest allowable noise to cover the detection range according to the SARPs (CONUS threat space) with a single baseline is <9 mm. The determination of figures on the test metric noise is on going. During initial evaluations of field measurements conducted by Thales, s. [56] an overbounded $\sigma_{\Delta^2\phi}$ of 5 mm was derived. Even if this value is comparable to previously mentioned noise values – in [26], a value of 6 mm is given – this value is may be optimistic, since on airport influences are not fully covered.

Siting implications resulting from carrier phase based ionospheric monitoring were also addressed in [26]. The paper assumes the already mentioned 6 mm standard deviation for the test metric noise and the detection range according to SARPs (CONUS threat space).

The paper also addresses the resulting test carrier phase double difference noise as key parameter driving the feasibility of the monitor. For the given noise level of 6 mm, baseline lengths between 200 m and 400 m were seen as useful. As will be shown later even somewhat smaller baseline lengths might be desirable (at least in addition) to increase the detection range of the ionospheric gradient monitor. Furthermore, the need to orient the baselines along runway orientations is addressed and the need for redundancy is mentioned.

Two possible layouts providing detection for multiple runway orientations, as well as redundancy were introduced. First, a square layout with a baseline length of 283 m, and as second variant a Parallelogram layout was introduced [26].

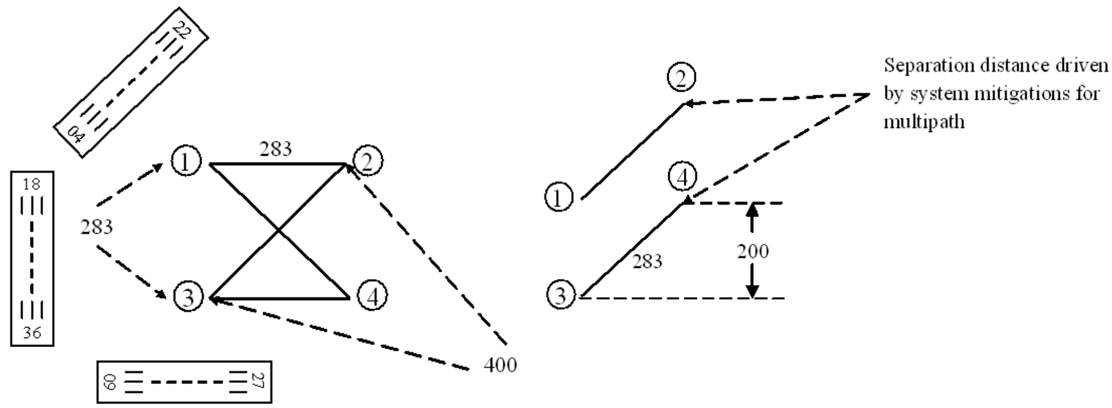
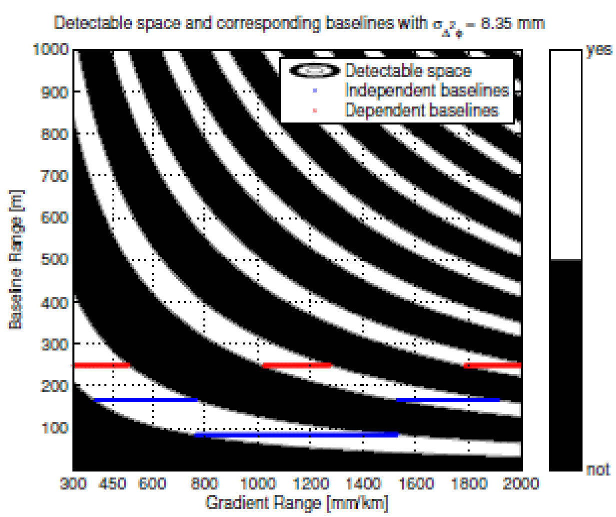


Figure 5-24: GBAS Reference antenna layouts for spatial ionospheric monitoring [26]

As mentioned before, the detection range required by SARPs may be exceeded in some regions on the world. Thus, an increased threat space up to 2000 mm/km was proposed in [59].
This increased detection range has some influences on the siting with respect to the spatial ionospheric gradient monitor, since a single baseline may not be able to cover the entire detection range.

In [63] it was proposed to combine baselines in order to cover the whole range of ionospheric gradients to be detected. For a configuration with four receivers and an assumed test metric noise of 8.67 mm, three baseline combinations – those of the direct or independent baselines of adjacent antennas – were considered. This led to the combination of baselines with separations of b1: 219.9m, b2: 116.8m, b3: 62.03m.

During Thales' further investigations on the GBAS GAST D spatial ionospheric monitor a systematic search algorithm was developed, which derives optimal baseline combinations. The search by this tool is performed under consideration of dependent baselines. This means those baselines, which will result for non-adjacent antennas and is configurable to consider redundancy aspects. An example of such a baseline combination result heading towards maximum detectability with anticipated worse noise conditions is given in Figure 5-25.The assumed test metrics noise standard deviation is 8.35 mm.



(a) 3 baselines combination

Figure 5-25: Optimal Baseline combinations for $\sigma_{\Delta^2\phi}$ = 8.35 mm

For lower $\sigma_{\Delta^2\phi}$ the baselines can cover the whole threat space anyway, but their combinations should be recalculated, to find the optimal antenna separation. Nevertheless the direct application of these optimal baseline combinations has some disadvantages and their direct application is therefore doubtful.

One of the reasons that three or four reference receivers and antennas are used in GBAS is, that they provide redundancy if one station fails. Furthermore, the calculation of the mean of the PRCs reduces their noise. For the carrier phase based mitigation scheme, redundancy would be desirable, too. However, because for one baseline two receivers are needed and no baseline exist, that covers the whole extended threat space, a failure of one receiver leads to some gradients that cannot be detected anymore. This would lead to an increased Pmd for certain gradients. In order to establish redundancy, either additional antennas have to be used or the required measurement quality has to be improved significantly.

With the use of optimised baseline combinations to cover the extended detection range the antennas are arranged in a straight line, if independent baselines or four receivers are used. Otherwise the length of other baselines must be projected. If the baselines are perpendicular, there exists a corner case for some front propagation directions were no gradient could be detected by at least one baseline. Thus, each baseline would have to be able to cover the whole detection range. For the extended detection range it is doubtful to be achievable. Second, the receivers shall be perpendicular to the worst-case wave front and thus aligned with the runway for which GAST D service shall be provided. A receiver line, which is parallel to the wave front, experiences no gradient because every station suffers from the same delay. Furthermore siting restrictions resulting from other influences – multipath, RFI – have to be considered for the baseline search.

It has also to be considered that the results derived for such optimal baseline combinations are only valid for a single value of the test metrics noise. Further investigations are necessary to confirm that the assumption of a single value is correct. Initial investigations indicate that certain differences between the antenna pairs may be evident. Furthermore, other siting restrictions are applicable – like minimum separations from multipath considerations. And finally, these results are valid for a straight line of antennas, providing no redundancy. The situation gets worse, when non parallel runway layouts have to be considered. Possible solutions could be based on overlapping the detection ranges of the single baseline combinations. Multiple runway directions would have to be covered by the projection of the straight line layout to the approach directions. But it needs to be considered that these means might require to lower the test metric noise.

With regard to code based monitoring means it can be assumed that these will serve as additional methodologies, having the potential to overcome the carrier phase based detection for the extended detection range. Due to the relatively large baseline lengths which will result, it can be assumed that such detection schemes use additional antennas. For which the 5 km siting restriction is also applicable. Below this maximum 5 km baseline length it is possible to trade-off between minimum detection by code based monitor and baseline length.

6 Siting process

The siting process described here is mainly derived from the ED-114 [1], the FAA Siting Handbook [24] as well as the ICAO Doc 8071 Vol. II [25].

This process consists of the following steps:

- Site Selection
- Site Qualification
- GBAS VDB channel assignment
- Installation
- Survey of the reference points
- Site Acceptance of the installed equipment

This step approach normally involves the service provider, the equipment manufacturer, the airport authority and civil aviation authorities. A siting team should be set up at an early stage to make sure that all local requirements and processes are taken into account while finding a site that will meet the overall GBAS system performance requirements defined in ICAO Annex 10 with comfortable margin. Explicit site requirements are further described in section 4, while general guidance and methods for site selection and site qualification are described hereafter.

The figure on the next page depicts the overall siting process.

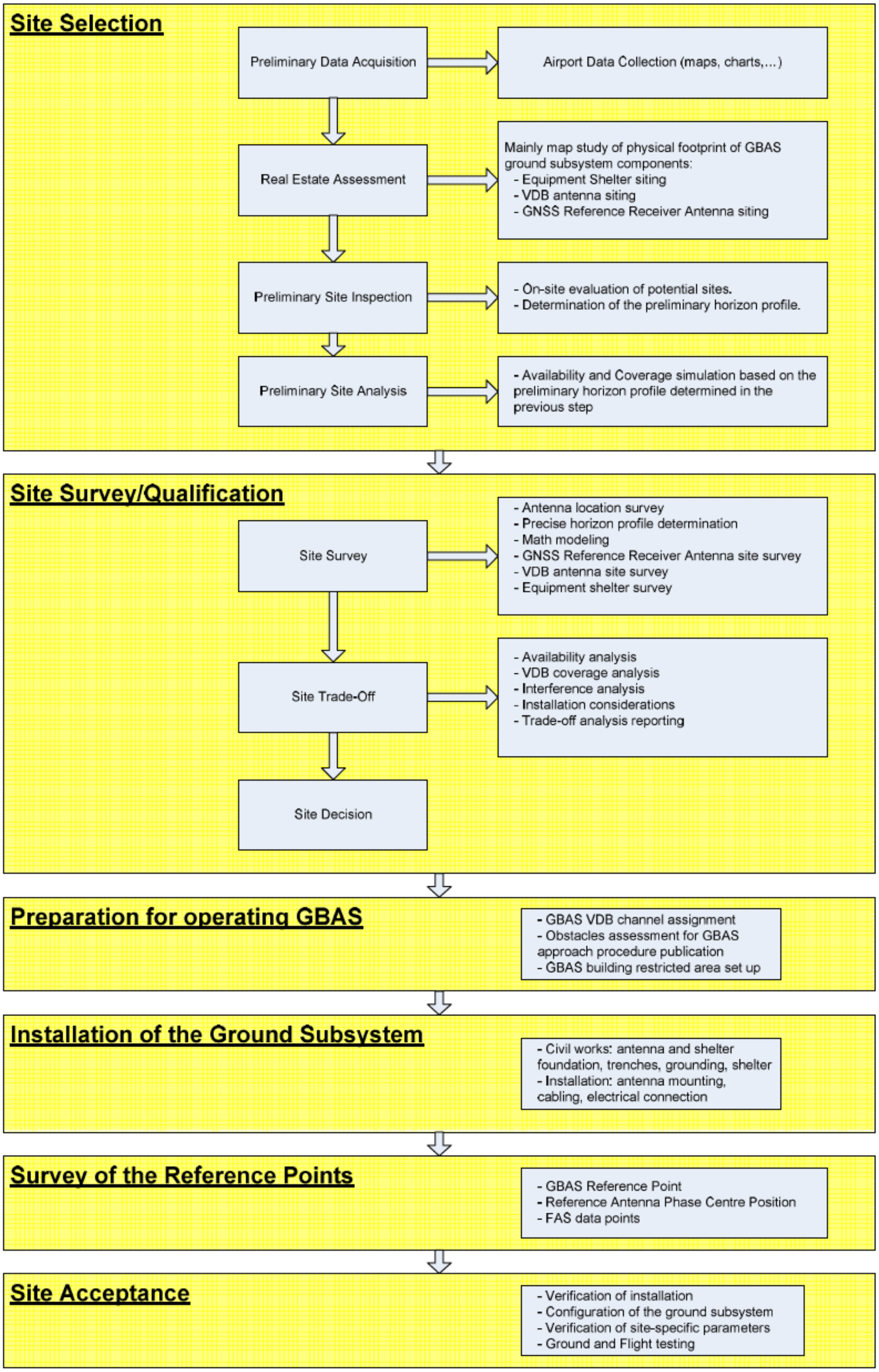


Figure 6-1: Overall GBAS siting process

6.1 Site Selection

6.1.1 General guidelines

The GBAS ground equipment Site Selection is typically done by a service provider and/or the airport.

The purpose of the Site Selection is to identify candidate sites that have potential for meeting system and operational requirements. This Site Selection represents a real estate elimination process that involves a complex set of trade-offs. These include operational requirements (like GBAS coverage volume), equipment requirements (like LOCA for GNSS and VDB antennas, minimum separation distance between antennas, etc.) and other requirements like availability of power and communication lines, site access and security. In addition, the interference environment of the sites has to be checked. For the selected sites all necessary information (e.g. map, obstacles, power and telecommunication lines, frequencies, etc.) is gathered and documented.

The objective of this process is to identify a small number (preferably 3) of potential site locations that represent the best of all factors considered. Finding and evaluating appropriate candidate sites should be done by a combination of map studies, on-site inspections and measurements, and possibly modelling and analysis. In general, all possible sites within three nautical miles of each supported runway end should be considered and evaluated against the guidelines defined in the following paragraphs.

It is recommended to site GBAS in an open, undeveloped area of an airport, but still within the airport perimeter. This minimises problems with RF interference, airport operations and security. However, in some cases, rooftop installations may also allow a good level of service provided the GNSS reference antennas can be sited in a clean multipath environment. In addition, various architectural options exist to deal with site challenges, such as VDB antenna diversity and GNSS reference receiver remoting. Exercising these options will affect ground facility complexity and cost, but may be well worth the investment given the absence of better site alternatives. The candidate site should provide for a VDB transmit antenna location that will meet the criteria described below, including sufficient space to build an equipment shelter within a few meters of the VDB antenna. The area around the VDB transmit antenna should also provide for several suitable GNSS reference antenna locations.

The Site Selection process consists of a Preliminary Data Acquisition, a Real Estate Assessment, a Preliminary Site Inspection, and a Preliminary Site Analysis. The results of the Site Selection are documented in the Preliminary Site Survey Report.

6.1.2 Preliminary Data Acquisition

The purpose of the Preliminary Data Acquisition is to gather all information required to support initial site selection. The gathered information should include:

- Airport Clearance Charts.
- Topographic Charts for the airport and full service coverage area for the GBAS ground station.
- Airport Layout Plan.
- Airport Planning Documentation (e.g., 10-year plan).
- Location of geodetic survey monuments, i.e. Primary Airport Control Stations (PACS) and Secondary Airport Control Stations (SACS).
- Obstacle free zones (OFZ), runway end safety areas (RESA), and obstacle limitation surfaces (OLS).
- Description of existing Air Traffic Control (ATC) facilities, navigational aids (NAVAIDS) lighting and power sources.
- Airport conduit and cable information.

- Ground traffic patterns.
- Run-up and jet blast areas.
- Determination of the Landing Threshold Point (LTP) and minimum glidepath.
- Airport property lines.
- Instrument Approach Procedures (IAPs) defining existing and proposed approach procedures to the airport and identifying obstacles in the terminal area.
- Noise abatement regions, procedures, and plans.
- Restricted airspace.
- Existing and future traffic patterns.
- Any required alteration to proposed flight paths.
- Aerial photographs of the airport and surrounding areas.

6.1.3 Real Estate Assessment

The purpose of the Real Estate Assessment is to obtain an initial list of prospective sites that merit further investigation. The Real Estate Assessment process should involve the study of maps, charts and other data listed under Preliminary Data Acquisition.

These studies should include the identification of areas that can support the physical footprint of the equipment, including consideration of the siting criteria expressed in section5.

This Real Estate Assessment process will assist in defining potential siting areas in preparation for the Preliminary Site Inspection.

6.1.3.1 VDB Antenna Location siting

The successive and complementary steps should be normally applied to determine suitable locations for the VDB Antenna:

- o Identify VDB Antenna locations as the obstacle limitation surfaces (S2) are protected
- o Identify VDB Antennas locations as the coverage volume, the maximum field strength requirements and the LOCA (S3) are met

It must be noted that potential airport expansion should be also considered (S9) in the reflection.

6.1.3.2 GNSS Reference Receiver Antennas Siting

The successive and complementary steps should be normally applied to determine suitable locations for the GNSS Reference Receiver Antennas:

- o Identify GNSS Reference Receiver Antennas locations as the obstacle limitation surfaces (S2) are protected
- o Identify possible sites where GBAS Reference Point is located no more than 5 km from any LTP (S4)
- o Identify GNSS Reference Receiver Antennas locations as the individual horizontal/elevation mask (S5) value is acceptable
- o Identify GNSS Reference Receiver Antennas locations to limit multipath as much as possible and LOCA is respected (S6)
- o Identify GNSS Reference Receiver Antennas locations as the separation distance and the specific arrangement between the GNSS Reference Receiver Antennas (S7) is fulfilled

- o Identify GNSS Reference Receiver Antennas locations as far as possible from public areas (S13)

It must be noted that potential airport expansion should be also considered (S9) in the reflection.

6.1.3.3 Equipment shelter siting

Siting of the shelter should be considered after possible locations for the GNSS Reference Receiver part and the VDB part has been identified.

The successive and complementary steps should be normally applied to determine suitable locations for the equipment shelter:

- o Identify equipment shelter locations as the obstacle limitation surfaces (S2) are protected
- o Identify equipment shelter locations where the relative distance to either the RRA or VDB antenna is a balance between two factors:
  - the shelter shall be sited far enough away from the RRA or VDB antenna so that it is not a source of unacceptable multipath or signal blockage. If the shelter penetrates a LOCA surface (S6), the system performance impact shall be analyzed through mathematical modelling.
  - the shelter shall be close enough to the RRA and/or VDB antennas so that communication and/or RF cables do not exceed requirements for maximum cable length

It must be noted that potential airport expansion should be also considered (S9) in the reflection.

6.1.4 Preliminary Site Inspection

The purpose of the Preliminary Site Inspection is to define the siting environment in detail in order to perform comparative trade-off studies between potential sites. The Preliminary Site Inspection will also be used to refine data collected during the Real Estate Assessment. The Preliminary Site Inspection process shall involve on-site evaluation of potential sites identified during the Real Estate Assessment. The data collected shall include terrain features, potential sources of multipath and shadowing, land availability, proximity of power, environmental impact, and site access. This initial data collection shall include a preliminary horizon profile (using a portable or handheld instrument such as an inclinometer), distance measurement to potential sources of multipath and shadowing, an estimate of the site location using a handheld GPS receiver, and a panoramic photograph at the proposed antenna sites.

6.1.5 Preliminary Site Analysis

The purpose of the Preliminary Site Analysis is to identify the sites that will be considered in the final site selection process. The Preliminary Site Analysis shall involve the review of data collected during the Real Estate Assessment and the Preliminary Site Inspection. The analysis shall consist of availability and coverage comparisons based on the preliminary horizon profiles at the RRA and VDB antenna sites respectively. The availability results can be determined using a Computer Availability Model.

6.2 Site survey/qualification

6.2.1 General Guidelines

The site qualification is typically performed by the ground station manufacturer and build on the information obtained during site selection.

During site qualification the ground station manufacturer has to make sure that the required performance at the finally selected site is fulfilled under all environmental and operational conditions of the airport. Therefore, the manufacturer receives the information about the pre-selected sites and conducts tests at candidate sites with the original GNSS antennas and receivers installed on a temporary platform. Careful planning and co-ordination is necessary to ensure that sufficient data can be collected to establish that the commissioned installation will support the desired level of service. In particular, antenna height tradeoffs and multipath assessments should be confirmed with manufacturer specific data and tools (VDB and GNSS). In addition, since multipath measurements will only be conducted over a few days, possible effects of seasonal variation should be considered. For example, summer foliage may mask multipath effects that are present in winter. Different airport operation (e.g. approach direction, usage of taxiways) should also be taken into account.

The VDB coverage resulting from proposed transmitter antenna position should be checked. At the end of the site qualification the manufacturer will commit himself on a final installation plan defining all necessary installation details e.g. the entire antenna positions (antenna in absolute WGS-84 co-ordinates) including the antenna heights etc.

As soon as the final antenna locations and the installation details are available, one can initiate frequency assignment and prepare for civil works.

6.2.2 Site Survey

The purpose of the Site Survey is to gather technical data at each prospective site chosen during the Site Selection process to aid in the Site Acceptance. The Site Survey shall consist of an Antenna Location Survey, Precise Horizon Profile, Math Modelling, GNSS RRS and VDB data collection, and Shelter Site Survey.

6.2.2.1 Antenna Location Survey

The antenna position shall be determined for each prospective antenna site considered for the Site Survey. The survey accuracy shall be at least ±25 cm relative to the PACS or SACS. The survey coordinates shall be used to identify prospective antenna sites, as an input to the GBAS ground subsystem models, and to identify selected site locations during installation.

Note: The antenna location survey refers to the survey required for antenna locations during Site Survey. Precise survey requirements for the GBAS ground subsystem antennas during installation are not detailed here.

6.2.2.2 Precise Horizon Profile

A precise horizon profile shall be generated for each prospective antenna site using precision survey equipment. The precise horizon profile shall include distance measuring to trees that are within 500 meters of the candidate antenna sites. The recording instrument shall be set up at the candidate antenna phase center location. Readings shall be recorded for any object that is greater than two degrees in elevation relative to the recording instrument. In addition, these objects shall be identified by name and salient characteristics (e.g., materials, roof pitch). The distance to potential sources of multipath and shadowing shall also be measured. The recording of the azimuth and vertical angles shall be taken to the nearest degree. The horizon profile shall be used as an input to the GBAS ground subsystem math models.

6.2.2.3 Math Modelling

The manufacturer shall conduct math modelling to estimate performance at each prospective site. The results shall be provided to the service provider via the Site Survey Report.

Data gathered during the Site Selection and Site Survey shall be used as inputs to the model. The data shall include antenna coordinates, antenna height above local ground, horizon profile, RMS_{pr_gnd}, and GRP to LTP distance. The data collected during Site Survey shall be used to validate the model results.

6.2.2.4 GNSS Reference Receiver Antenna Site Survey

The GNSS RRA Site Survey shall consist of the precise horizon profile described above and shall also include ranging source data collection described hereafter. The precise horizon profile shall be used as an input to the availability and RRAs math models; the ranging source data collection shall be used to evaluate the pseudorange errors at the prospective sites and to perform multipath measurements.

6.2.2.4.1 Ranging Source Data Collection

The ranging source data collection shall include temporary installation of the GNSS reference receivers at each proposed RRA site (for all three proposed configurations). The Ranging Source Data Collection methodology shall be agreed by the service provider. The test description shall include test setup, test duration, and data collection. The associated statistical confidence shall be quantified.

6.2.2.4.2 RRA Interference Data Collection

Controlled tests shall be conducted to determine if the selected RRA site has acceptable levels of interference to the GPS signal.

To characterize the RF environment, an RRA shall be located at the proposed site on a temporary support and the data shall be collected.

The nominal interference environment is defined in section 3.7 of Appendix B of ICAO Annex 10 [14]. The signal levels are specified at the antenna port i.e. at the input of the pre-amplifier. They include a minimum standard antenna gain above 5 degree elevation angle of -4.5 dBic. For non-standard antennas with a different minimum gain above 5 degree elevation angle or for RF components that comprises both the antenna and the low noise amplifier, the signal interference levels can be adjusted accordingly as long as the relative interference-to-signal level is maintained.

As the antenna pattern and/or pre-amp design may contribute to interference susceptibility at a particular location, it is strongly suggested that the test includes the whole set of actual RF components (antenna, bandpass filter, and preamp) that will be used at the selected site.

The test setup shall consider identification of possible intermittent interference sources.

The RRA Interference Test methodology shall be agreed by the service provider. The test description shall include test setup, test duration, and data collection. The associated statistical confidence shall be quantified.

6.2.2.5 VDB Antenna Site Survey

The VDB antenna Site Survey shall consist of the precise horizon profile described above and may include VDB field strength measurement and Interference Data Collection.

The precise horizon profile shall be measured at each proposed VDB site and shall be used as an input to the VDB math model.

A VDB Site Survey ground and/or flight test may be also performed in case of doubts on the coverage prediction results. These tests will verify the coverage attained at the selected site. According to the results obtained in T016, the prediction of the VDB field strength is more accurate for the approach path than for ground/runway coverage. Therefore, VDB ground coverage measurements are highly recommended to check that the VDB field strength above the runway surface is sufficient.

The VDB Interference Analysis and Data Collection will verify that the VDB is not interfering with or interfered by existing airport systems. All VDB testing will be coordinated closely with airport and ATC officials. Prior to any extended testing, controlled tests shall be conducted with ATC personnel to ensure no potential for disruption of airport operations.

6.2.2.5.1 VDB Site Survey Flight Test

If needed, the VDB Site Survey flight test shall include, at a minimum, flight procedures that verify field strength requirements within the coverage volumes.

The Site Survey flight test shall be conducted using the GBAS VDB subsystem installed temporarily at the selected site. “Canned” VDB messages, formatted in accordance with RTCA/DO-246D [66] shall be transmitted from this location and received by the flight test aircraft. The airborne data collection system shall record the level of the received VDB signal (Horizontal polarization). The airborne data collection system shall also have the capability of detecting any lost or failed messages in post-processing to assess signal degradation and/or outages and to provide additional validation of field strength results.

The VDB Site Survey Flight Test methodology shall be agreed by the service provider. The test description shall include test setup, flight profiles, number of approaches, data collection, and data analysis.

6.2.2.5.2 VDB Site Survey Ground Coverage Test

The Site Survey ground coverage test shall be conducted using the GBAS VDB subsystem installed temporarily at the selected site. "Canned" VDB messages, formatted in accordance with RTCA/DO-246D [66] shall be transmitted from this location and received by the ground measurement vehicle. The ground measurement vehicle data collection system shall record the level of the received VDB signal at 12 ft above the runway surface. Measurement results at 8 ft above the runway surface are also expected.

Special attention should be paid to use a calibrated GBAS receiver, calibrated measurement antenna, and calibrated cables. The ground measurement vehicle data collection system shall also have the capability of detecting any lost or failed messages in post-processing to assess signal degradation and/or outages and to provide additional validation of field strength results.

6.2.2.5.3 VDB Interference Analysis and Data Collection

An analysis should primarily determine if potential interference on or from other airport systems could occur. Existing ICAO Annex 10 geographical separation criteria between GBAS and VOR as well as the draft geographical separation criteria between GBAS and ILS and GBAS and VHF-COM established by 15.3.6 D24 [15] should be checked.

If the analysis shows that the necessary separation is not guaranteed controlled tests shall be conducted. The tests should concentrate on expected issues: for instance, influence on VOR monitor that generally presents wide bandwidth may be particularly assessed. The tests shall be conducted with the VDB antenna installed temporarily at the proposed location and height. The VDB test setup shall include the same type equipment (i.e., same part number) that will be installed at the site. In addition, the power budget variables (e.g., RF cable loss, transmitter output power) shall be the same as the proposed installation.

A simple check with a spectrum analyzer in the VHF NAV band between 108 MHz and 117.975 MHz will be also conducted. This could help to identify unknown sources or intermodulation products (especially from FM broadcast) that may affect the reception or the monitoring of the VDB.

6.2.2.6 Equipment Shelter Site Survey

The Equipment Shelter Site Survey shall consist of a precise survey of the proposed shelter location, and an analysis to determine if the site notably violates the siting criteria S1, S2 expressed in section 4.1.

6.2.3 Site trade-off analysis

The Site trade-off Analysis shall involve analysis of data collected during the Site Selection and the Site Survey. This will be concluded by a recommendation made by the manufacturer on the best possible site for GBAS ground subsystem installation.

6.2.3.1 Availability Analysis

The service availability attained at the prospective sites shall be estimated using the GBAS Availability Model. The Availability Analysis will require determination of the Ranging Source Broadcast Mask and the GNSS RRS performance curve. The availability analyses shall be based on the worst-case subset of three (3) RRS's. The optimised 24 GPS constellation defined in RTCA/DO-229D Appendix B shall be used.

6.2.3.1.1 GPS Reception Mask / Ranging Source Broadcast Mask Determination

The GBAS ground subsystem GPS Reception Mask shall be used to determine the Ranging Source Broadcast Mask which shall be an input to the availability model. The GBAS ground subsystem GPS reception mask shall be based on the precise horizon profile described in Section 6.2.2. The horizon profile shall be inflated, where applicable, to account for a five-year nominal tree growth of six inches per year. The distance to trees recorded during the Site Survey shall be used to determine the inflated elevation angles. The Ranging Source Broadcast Mask shall be computed from the GBAS ground subsystem GPS Reception Mask by taking into account the time required for the RR data to be able to be used for the computation of measurement blocks after a satellite is acquired.

6.2.3.1.2 GNSS RRS Performance Curve Determination

The GNSS RRS performance curve shall be an input to the availability model. The GNSS RRS performance curve shall be based on the estimation of RMS $_{pr\_gnd}$, using the GBAS ground subsystem RRS model results, ranging source data collected during the Site Survey and processing techniques (e.g. as described in ED-114 [1]).

6.2.3.2 VDB Coverage Analysis

The VDB coverage analysis shall be based on the VDB model results, precise horizon profile and VDB Site Survey ground and flight test results if available. An initial assessment of the quality of each proposed VDB site shall be made based on the line-of-sight (LOS) to the primary runways' approach coverage volume and other required coverage areas. The proper antenna height shall be chosen to meet field strength requirements throughout the required coverage volumes. Although this initial analysis is based on LOS, it is recognized that there may be constructive and destructive interference that may impact the VDB coverage volume.

The analysis of test data will provide a more thorough coverage evaluation throughout the required coverage volumes. If deemed necessary the Site Survey VDB coverage analysis shall be supported by field strength analysis based on ground and/or flight data.

6.2.3.3 Ranging Source Pseudorange Error Analysis

An analysis of the pseudorange errors at each antenna site shall be performed using the guidelines in Section 5.3. The analysis shall include the generation of error statistics that will be compared to the requirements curves. Analysis shall also be conducted to identify sources of excessive multipath.

6.2.3.4 Interference Analysis

6.2.3.4.1 RRA Interference Analysis

An analysis of the interference environment shall be performed using the data collected in Section 6.2.2.4.2.

The potential impact of RFI signals in the GNSS band can be assessed by a comparison of the received spectrum with the interference masks for GNSS receivers specified in ED-114 [1] Appendix E.2.1.1. Continuous wave and narrowband (<10 kHz) interference signals exceeding those levels for more than a few seconds are not acceptable as they may affect service availability. Since such signals are most critical (apart from spoofing signals) it should be ensured that any already present interference signals are detected by the methodology described in ED-114 [1] chapter 5.13. Signals with other properties e.g. broadband signals or pulsed signals usually have less impact. Since there is no general method to assess the interference effect of arbitrary signal types an expert judgement is necessary to decide if the observed interference is tolerable or not. If it is not possible to detect and eliminate the interference source or to move to other unaffected antenna locations it is recommended to perform receiver susceptibility tests. The interference masks for band-limited noise in ED-114 [1] Appendix E.2.2 are intended for receiver testing and apply to in-band interference signals regardless of their centre frequency. The threshold for pulsed signals in ED-114 [1] Appendix E.2.3 may serve as a first estimate. An adequate method is a receiver susceptibility test. A signal generator is used to reproduce the interference signals and it is checked whether typical GNSS receivers will experience intolerable degradations or errors. The most sensitive receiver output value to detect degradations is the carrier to noise density ratio C/N_0 of the tracked satellites. The C/N_0 values of a GNSS receiver may also provide a first indication of the harmfulness of a detected interference signal if a GNSS receiver is operating at the same location and simultaneously with the outdoor interference test equipment.

If interference signals are detected it is useful to repeat the measurements at another nearby location (separated by at least 300 m) to determine if the level of the interference source varies with position. In this case the interference source may be a weak source close to the site or an interference source with a higher output power at a greater distance. For a better localisation of interference sources a direction finding capability (ground mobile and/or airborne) of the interference measurement equipment is useful. If the interference environment does not meet the interference mask, the interference source shall be identified and mitigation strategies shall be developed. If the interference signal is in conformance with its licensed operating signal parameters, and mitigation of the interference is not feasible, the RRA will need to be relocated or additional filtering added.

Special attention should be also paid to the potential interference caused by GNSS repeater or jammer as explained in section 4.2. It is desirable to locate the GNSS receivers away from the public areas (public roads, airport terminals etc) to reduce the possible impact of interference. Typically, since GPS L1 is a protected frequency band, the problem would be reported to the national spectrum management authority to find and eliminate the interference source. For fixed interference sources there is a fair chance to have the problem removed in a short timeframe, whereas this might be more complicated for mobile interference sources.

6.2.3.4.2 VDB Interference Analysis

An analysis of potential interference to other airport systems shall be performed using the data collected in Section 6.2.2.5.2. If it is determined that the VDB is interfering with other airport systems, corrective action shall be identified to mitigate the interference to acceptable levels.

6.2.3.5 Installation considerations pertinent to siting

6.2.3.5.1 Power considerations

Proximity of power shall be considered when making the GBAS ground subsystem siting decision. The impact of proximity to power on the siting decision is primarily a cost impact. The cost of obtaining power at a prospective location from a prospective power source shall be weighed against other siting considerations when conducting the trade-off analysis between prospective GBAS ground subsystem sites.

6.2.3.5.2 Cable run considerations

Trenching and maximum cable length requirements should be considered when making the GBAS ground subsystem siting decision. Utilization of existing cable runs shall be considered.

The amount and feasibility of cable trenching shall be considered when identifying prospective GBAS ground subsystem sites. The impact of trenching on the siting decision is primarily a cost impact. The cost of cable trenching shall be weighed against other siting considerations when conducting the trade-off analysis between prospective GBAS ground subsystem sites.

The maximum cable length will be dictated by the maximum acceptable signal loss and is dependent on the type of cable and the nature of the transmitted information (i.e., digital or RF). The maximum cable lengths may impose restrictions on the prospective locations for any equipment connected to the cables. This may include the RRs, RRAs, VDB antennas,, and ATCU.

6.2.3.5.3 Site access considerations

Proximity of site access roads shall be considered when identifying prospective GBAS ground subsystem sites. The impact of proximity to site access roads on the siting decision is primarily a cost impact. The cost of building new access roads at a prospective location shall be weighed against other siting considerations when conducting the trade-off analysis between prospective GBAS ground subsystem sites.

6.2.3.5.4 Site environmental analysis

The Site Environmental Analysis shall involve identification of locations of environmentally sensitive areas such as wetlands, floodplains, historical or archaeological sites, and endangered species habitats. Whenever possible, siting engineers shall select alternative sites to avoid these environmentally sensitive areas.

6.2.3.5.5 Equipment environmental and maintenance considerations

Equipment environmental considerations shall be considered when the proposed equipment site is in an existing facility other than the standard GBAS ground subsystem equipment shelter. The impact of equipment environmental considerations on the siting decision is primarily a cost impact. Prospective non-standard GBAS ground subsystem equipment sites may be unsuitable or may require modifications to meet the equipment environmental and maintenance requirements.

When existing facilities are used to house any GBAS ground subsystem equipment, the facilities shall be environmentally controlled and compliant with current safety and health requirements. The building/structure shall have as a minimum, sufficient room for routine maintenance and repair to be performed within the required time period.

6.2.3.5.6 Cost analysis

All data necessary to estimate the cost of establishing an GBAS ground subsystem at each proposed location shall be collected during the Site Survey. Some of the items that require special attention due to their potential impact upon the cost of site development include: GBAS ground subsystem configuration, soil analysis and bearing capability, trenching, drainage, grading, access roads, utility service, and earth resistivity.

6.2.3.6 Trade-off Analysis Reporting

The manufacturer shall present the comparison analysis between at least three prospective sites to the service provider. The manufacturer shall provide the results of the siting trade-off analysis in the Site Survey Report.

The manufacturer shall use all pertinent data and analysis for each prospective site to generate a trade-off analysis between the sites. The manufacturer shall identify any requirements that are at a high risk of not being met at the prospective sites. The manufacturer shall propose siting mitigation strategies that may improve the performance at any of the prospective sites.

6.2.4 Site Decision

Based on the elements recorded in the Site Survey Report, the service provider will select the site for GBAS ground subsystem installation.

6.3 Preparation for operating GBAS

The following activities are not directly related to siting but they constitute necessary preliminary steps for operating a GBAS system at a given airport. These activities can be conducted in parallel.

6.3.1 GBAS VDB channel assignment

The GBAS VDB channel assignment must be conducted at an early stage to make sure that a frequency that meet the necessary separation criteria is available. Once the final site is chosen, the channel assignment process can start.
This should be carried out or co-ordinated by the national Frequency Management representatives from the EANPG-FMG (European Air Navigation Planning Group) for the candidate sites and is based on the separation distance criteria defined for GBAS in ICAO Annex 10. For a given candidate location, a search for acceptable candidate frequencies for the VHF Data Broadcast should be performed based on the above mentioned separation criteria between GBAS and existing ILS and VOR installations in the ARNS VHF band 108.00-117.975 MHz. Consideration of 15.3.6 T024 and ICAO on-going work on GBAS VDB frequency coordination criteria update should be also paid. More details can be found in [15].

If no suitable frequencies can be identified and a frequency change for existing ILS or VOR installations is the only option, then the impact to Localizer frequency paired DME-installations in the Band 960-1215 MHz has to be taken into account as well.

6.3.2 GBAS Building Restricted Area set up

Surrounding buildings may cause unacceptable interference to the signal-in-space in the service volume of CNS facilities. Therefore, States must define protection zones around the ground facility to prevent from adverse effect on the availability or quality of the CNS signal and also must assess all building activities in those protection zones.

The ICAO DOC 15 [67] developed by the European and North Atlantic Office of ICAO provides guidance material on the management of building restricted areas (i.e. protection zones) for CNS facilities. The document defines building restricted area (BRA) for the most common facilities and also enables member states to assess building applications to a known process. A generic and harmonised BRA is notably given for GBAS.

Once the final GBAS ground subsystem site has been determined, a local GBAS BRA must be set by the appropriate authority to evaluate all planning applications for building that may occur in the future.

6.3.3 Obstacles assessment for GBAS approach procedure publication

The GBAS approach procedure publication will require the calculation of the obstacle clearance altitude/height (OCA/H) as stated by ICAO PANS OPS [68]. The OCA/H calculation will imply the consideration of obstacles located in the vicinity of the airport. Identification of obstacles requires a complete engineering survey for all areas underlying the obstacle limitation surfaces. Such survey is generally conducted by governmental authorities with the co-operation of the airport operator.

6.4 Installation of the Ground Subsystem

6.4.1 Introduction

The installation of the ground subsystem can be split up into two sub activities:

1. Establishing the infrastructure
2. Installation of the ground subsystem

An overview of the process to establish the infrastructure is depicted in Figure 6-2. The infrastructure is normally the responsibility of the airport owner/operator. The shelter and foundations are built on the ground subsystem manufacturer's specifications. Cable ducts are dug according to the site survey report. During the readiness inspection at the latest, or as soon as any deviations become evident, the airport owner/operator must inform the ground station manufacturer of any deviations from the plan. For instance, if for some reason the cable ducts cannot be made in a straight line, action must be taken so the cables can have the correct length.

A complete GBAS installation will normally consist of the following elements:

- A shelter housing the GBAS cabinet.
- Four GPS antennas.
- One VHF TX/RX antenna, typically located 15-40m from the shelter.
- A remote control and status unit in the engineering/technical room, and corresponding ATC unit in the approach control and the control tower.
- An MDT for maintenance and monitoring purposes.

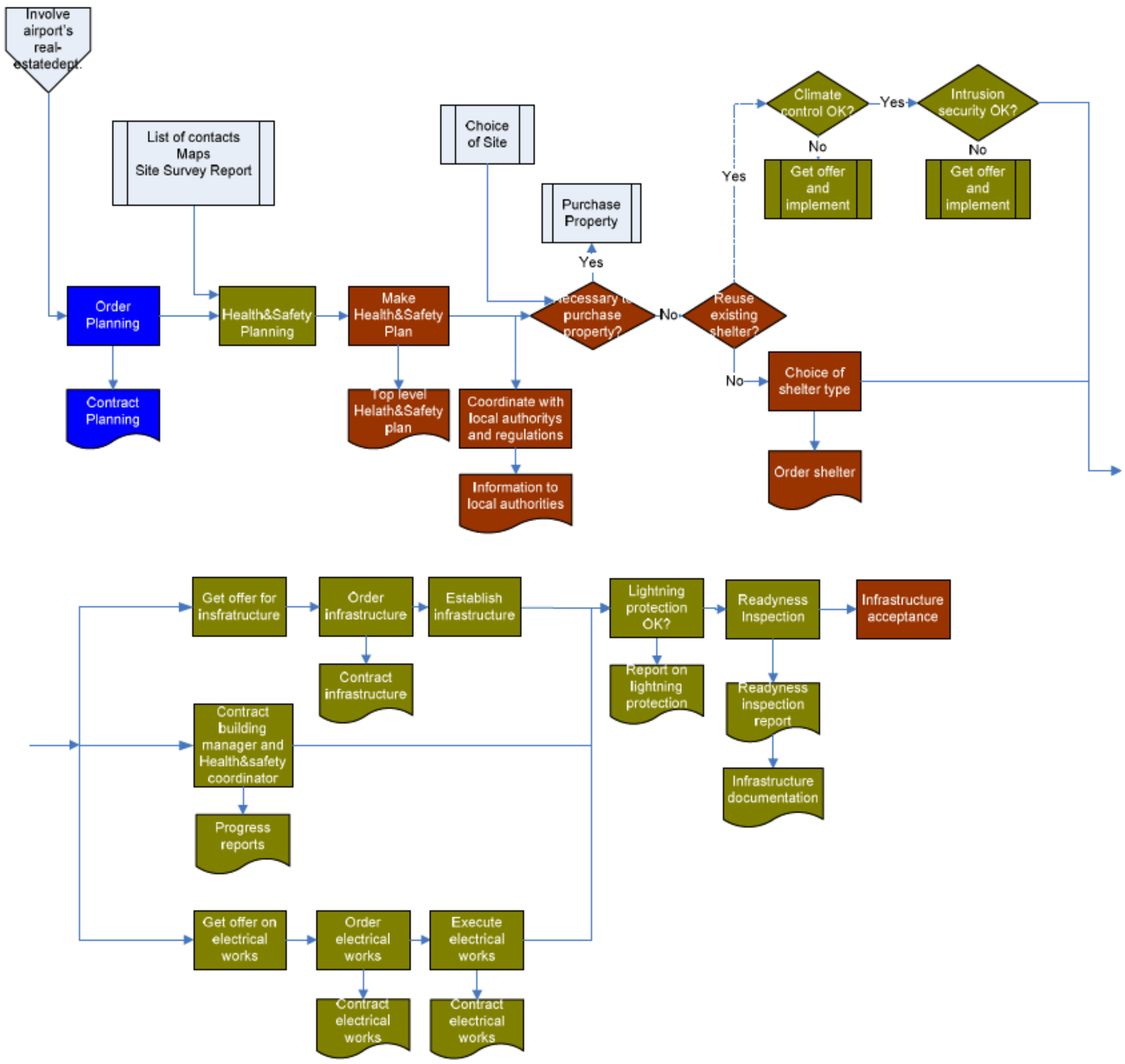


Figure 6-2: Establishing the infrastructure

The infrastructure/civil works normally include:

- Shelter including electricity and lightening protection
- Cable trenches including tubes and pulling threads
- Antenna foundations
- Communication lines

After the infrastructure has been established and accepted, the installation of the ground station can start. The ground station installation comprises:

- Masts
- Antennas
- Ground station including UPS or batteries
- Local Maintenance Data Terminal (MDT)
- ATC Control & Status Unit
- Remote Control & Status Unit (optional)
- Remote Maintenance Data Terminal (MDT) (optional)

6.4.2 Civil works

6.4.2.1 Antenna Foundations

Concrete foundations for the antennas are installed according to the airport owner's standard or according to manufacturer's specifications. The exception is if antennas are mounted on buildings or other structures, in which case the mounting arrangement must be specially adapted. Guide plates or templates for spacing of bolts are supplied by the ground station manufacturer. The base of the antennas should be within $\pm$ 1° of the horizontal, and the installation should be as stiff as possible. A requirement to the long term stability of the foundations may apply, driven by the ionospheric gradient monitor and the corresponding phase centre calibration scheme. At the time of writing, such a requirement has not been derived.

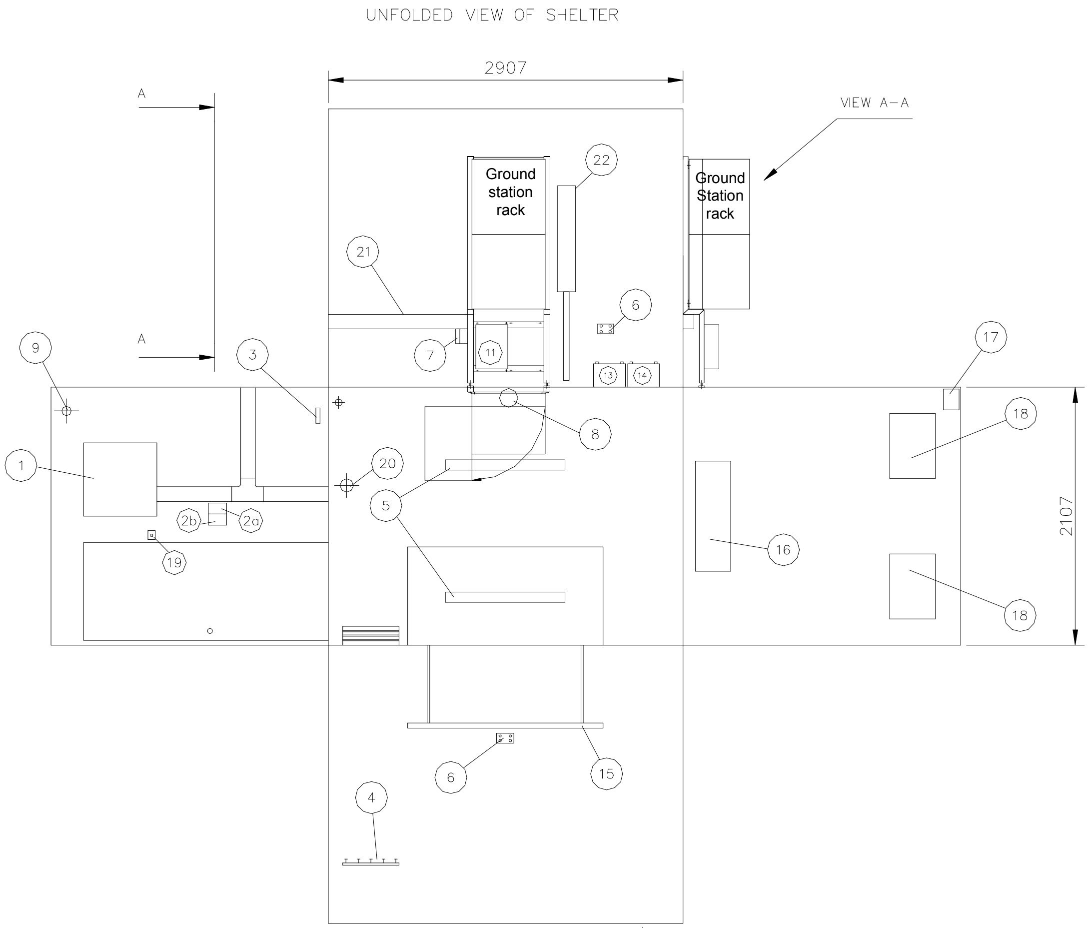
6.4.2.2 Cable trenches

Cable trenches should be dug in straight lines if possible. If this is not possible, the ground station supplier should be contacted immediately to assess impact of extended cable trenches. PVC tubes are laid in the trenches, typically at 0.5 m depth. 4" tubes are normally sufficient, but this is manufacturer dependent and may vary from installation to installation depending on whether more cables are combined in the same trench/tube. Two threads should be pulled through each tube: a pulling thread for pulling through cables, and a measure thread to be used to determine the exact length of the tube for production of cables.

6.4.2.3 Antenna grounding connections

This section is provided as guidance material. The Civil Work Contractor must take into account the local conditions and comply with any local regulations. Copper spikes should be driven into the earth at each of the antenna masts, and at the equipment shelter. General guidelines are that earth resistance is recommended to be less than 10 ohm, and shall not be more than 30 ohm, but this may depend on equipment type to be installed.
If it is chosen to connect the antenna mast to the shelter ground, a 35 mm^2 (minimum) bare copper wire should be used, and the copper wire should be laid in the cable ditch before filling.
The earth spikes and the copper wire will normally be provided and installed by a civil work contractor.

6.4.2.4 Shelter



1. Mains fuses/switch and group fuses (autom.)
2a. Telephone line teminal box
2b. Line protection for remote control
3. Ground connection
4. Hat rack
5. Flourecent lamps
6. Outlet 4–pole
7. Battery fuses (autom)
8. Tubes inlet/outlet
9. Ventilator outlet
11. Battery charger
13. Battery
14. Battery
15. Work bench
16. Heater (Not used when aircondition installed).
17. Thermostate controlled fan (when air cond. not used).
18. Air condition units
19. Light switch
20. Tube inlet for Power cables, Signal cables and Ground
21. Cable trunking

Figure 6-3: Typical shelter layout

Figure 6-3Figure 6-3 illustrates a typical shelter layout and serves as a guideline with respect to the items that need to be taken into account. Each manufacturer may provide his own layout guideline. In some cases, existing shelters may be reused. If so, such a guideline can be used to verify that the existing shelter can accommodate all the items required for the specific ground station installation.

Concrete foundations for the equipment shelter should be performed according to drawings from the shelter manufacturer. The Civil Work Contractor is responsible for the stability of the foundation observing the bearing capacity of the soil at the equipment site.
Adequate drainage shall be included to avoid water ingress under heavy rain conditions.

Copper spikes should be driven into the earth at the equipment shelter for grounding. Earth resistance is recommended to be less than 10Ω, and shall not be more than 30Ω.

The temperature and humidity inside the shelter must be kept within specifications given in the manufacturer's instruction. However, it is recommended to stabilize the temperature between 10 and 25°C, as this will normally increase the reliability of the equipment.

Shelter must be kept clean to reduce dust particles in the air, and there should be filters on air inlets.

The shelter should not house equipment that produces conductive gases. It is considered to be safe to use equipment with small amounts of conductive gases, such as lightning protection equipment, fluorescent lights etc.

It is also recommended that the floor in shelter is ESD proof. If not, a grounded static dissipative mat must be used whenever handling electronic modules.
The shelter is part of the physical security barrier and measures must be taken to prevent access of unauthorized personnel to shelter and antennas. Intrusion alarm may be considered.
Personnel health and safety precautions must be taken into account both for the installation work and for the permanent installation. For example, adequate fixture of racks must be in place.

6.4.2.5 Communication lines

The communication lines provide a possibility for remote monitoring and control of the ground station. An ATC Status unit is the only mandatory remote installation. This unit may also provide some basic control functions such as On/Off, reset etc. Remote Control and Status unit and Maintenance Data Terminal (MDT) are optional. Normally, communication lines are not installed specifically all the way from the shelter to the technical facilities at the airport. Rather, spare copper wires available nearby are used and modems are installed in order to convert to whichever protocol used by the ground station. The capacity of the communication lines may be limited, and the remote installations will have to be adapted to the capacity available. Normally the bandwidth used for the ATC (Control and) status unit is limited, whereas the MDT may require a higher bandwidth. It may therefore not be possible to install a remote MDT if the capacity of the communication lines is very limited.

6.4.3 Installation

6.4.3.1 Antenna mounting

The antenna heights must be determined during the siting process, and masts produced accordingly. The mounting of the masts, antennas and any additional equipment as required for the specific ground station type must take place according to the manufacturer's instructions. The exact GPS antenna positions need to be surveyed. It is recommended that this is done with the ones to be mounted as part of the GBAS ground station. If this is not possible, the positions must be corrected for difference in phase centre height. Some GPS antennas require a specific alignment relative to true north, and this must be taken into account when mounting the antennas. The antenna mounting should be such that vibrations are minimised. Depending on the individual manufacturer's error budget, the requirements may vary. For GATS D, the requirement will be driven by the Ionospheric Gradient Monitor and will be in the millimetre range.

Where required, in accordance with ICAO Annex 14, chapter 6, obstruction light may be fixed in the top of the VHF transmitter antenna.

6.4.3.2 Cables and connectors

Cable lengths have been determined during site survey, and need to be verified after the civil works have been completed in case trenches could not be placed where planned. Some cables have a minimum bending radius that needs to be taken into account during installation. Cable- and connector types are determined by the manufacturers. All outdoor connectors must be protected by shrinking tube or vulcanising tape after installation. All cables/connectors should be marked.

6.4.3.3 Lightning and overvoltage protection

Air termination spikes are recommended if the antennas are mounted on a location where it is exposed to direct lightning hits. For the GPS antennas, it may be difficult to mount the spikes on the antenna. In that case, if it is decided to use lightening protection, they could be mounted on a pole nearby. Over voltage protection at the antenna mast is recommended if the GPS antenna is exposed to nearby or direct lightning hits, and serves to protect the LNA of the GPS antenna or potentially the GPS receiver if mounted on the antenna mast. There should be over voltage protection at the intakes on the shelter wall. The protection circuits should be mounted at the wall of the shelter and have low impedance connection to shelter earth point. Line transient absorbers must be installed at the entrance of the communication lines, both in the shelter and remote. Coaxial protectors must provide DC feed through if supplying external equipment such as LNAs.

6.4.3.4 Grounding

All electrical equipment within the shelter must be connected to a common earth point. If the shelter ground is used also for the grounding of the antenna masts, they must be connected to the same common earth point. Electronic devices installed outside the shelter are normally dependent on working on approximately the same potential as the main rack. Therefore, common grounding or low ground resistance is important for the correct functioning of peripheral units.

6.4.3.5 Electrical Installation

The installation work shall be in accordance with good workmanship standards and follow the regulations given by local authorities, plus installation instructions from the manufacturers for special connectors. Wires inside shelter should be halogen free. All cables must be kept away from any sharp edges that can damage the cables.

The input voltage must be according to the manufacturer's specification, normally 230V AC (+/-20%), 45 – 65 Hz. The capacity must be enough to transmit in all allocated time slots + charging any potential batteries and driving other installations such as MDT and air-conditioning. A transformer must be used if the available input voltage is less than the minimum.

If power outages are a known problem in the area, this should be taken into account when choosing battery capacity and/or UPS.

6.4.3.6 Installation and connection of the GBAS ground station

This shall be done according to detailed instructions from the manufacturer. This instruction includes mounting of racks and other units, connection of cables and batteries, setting of jumpers (if any) and any potential calibration activities being necessary for the particular GBAS ground station. Some ground stations may allow for connection of external sensors for temperature, intrusion, antenna connection monitoring etc. and these are connected according to the manufacturer's instruction and ground station owners decisions.

It is recommended to perform a functional check of the installation if possible. However, at this stage, no configuration is stored in the ground station and this will normally prevent full operation of the ground station. If possible, coarse antenna coordinates and some default configuration could be configured in order to get the station running to verify correct installation. Any VDB transmission must be according to available permissions, and the station should be in maintenance/test mode.

6.5 Survey of Reference Points

6.5.1 General considerations

The service provider should set up appropriate processes to store and preserve the accuracy of all GBAS co-ordinate data. The survey can be performed with independent survey equipment, or with the actual installed antennas connected to survey equipment.

6.5.2 GBAS Reference Point Accuracy

The absolute accuracy of the GBAS reference point with respect to WGS-84 should be established.

The survey error of the GBAS Reference Point, relative to WGS-84, should be less than 0.25 m vertical and 1 m horizontal.

If the GBAS Reference Point is not one of the reference antenna locations, a durable survey marker should be installed to allow for future surveys, for example to survey reference points for a new FAS.

6.5.3 Reference Antenna Phase Centre Position Accuracy

The co-ordinates of the phase centre of each GNSS reference antenna must be surveyed relative to the GBAS Reference Point. This can be done by the service provider prior to site qualification.

For each GBAS reference receiver, the reference antenna phase centre position error shall be less than 8 cm relative to the GBAS reference point. This value includes at least the survey accuracy of the antenna location relative to the GBAS reference point, possible movements of these points, the mechanical flexure and the phase centre variations of the reference antenna itself.

Conversions to and from national reference datums should be avoided.

Besides the above stated generally applicable requirements on the GBAS reference antennas phase centre accuracy, tighter requirements can result for GAST D depending on a manufacturer's ground subsystem architecture and monitoring schemes. As an example, the carrier phase based implementation of the spatial ionospheric gradient monitor for GAST D may serve. The performance of this monitor will profit from highly accurate knowledge of the antenna phase centres. Depending on manufacturer's implementation absolute phase centre accuracies better than 1 cm will be required.

6.5.4 FAS data points Accuracy

The relative survey error between the FAS data points and the GBAS reference point shall be less than 0.25m vertical and 0.40 m horizontal.

6.6 Site acceptance

The Site Acceptance covers

- verification of the installation,
- verification of site-specific parameters,
- ground testing and
- flight testing/inspection.

After installation of the final equipment according to the installation plan and after configuration of all site-specific parameters the performance of the installed equipment is verified by ground test and flight test. In addition, the open site specific topics for personal health and EMC are tested.

6.6.1 Common GAST-C and GAST-D performance verification method

Guidance material on site acceptance as well as appropriate ground and flight tests to verify installed GBAS GAST-C system performance can be found in the GBAS Chapter of ICAO Doc 8071 [25].

Here only the main topics are addressed.

6.6.1.1 Verification of site-specific parameters

Site survey data has been used to define preliminary configuration parameters allowing to perform availability simulations and performance estimations. After installation, a refinement and derivation of a full set of configuration parameters is necessary.

This notably includes the following GAST-C broadcast signal-in-space integrity parameters:

- Ground pseudorange uncertainty σpr_gnd: preliminary value determined during design qualification should be confirmed as valid for the site
- Tropospheric delay and residual tropospheric uncertainty: appropriate values are determined by analysis of regional weather and atmospheric statistics, to ensure that errors are adequately bounded without unnecessarily inflating the protection levels
- Residual ionospheric uncertainty $\sigma vert\_iono\_gradient$: determined by an analysis of regional ionospheric statistics, to ensure that errors are adequately bounded without unnecessarily inflating the protection levels

Some of the monitors limits are also specific to the site. Therefore, a determination or a refinement of these monitors limits must be done.

6.6.1.2 Ground testing

The following list indicates the ground tests that should be conducted during site acceptance:

- Pseudorange domain accuracy evaluation (GAD Assessment)
- Evaluation of error correlation between RRs, estimation of the distribution of the errors.
- If the proposed equipment shelter location is within the RRA LOCA, its effect on system performance shall be evaluated
- Position domain accuracy functional test
- Continuity of Service performance demonstration of the installed equipment
- Data broadcast parameters content verification
  - Type 1, Type 2 and Type 4 message content

6.6.1.3 Flight testing

The following list indicates the flight tests that should be conducted for site acceptance:

- VDB coverage and verification of absence of interference in the VHF NAV band
- Resistance to interference of the ranging signal

For commissioning, also other aspects have to be considered.

6.6.2 Specific GAST-D performance verification method

In addition to the common verification activities with GAST-C, the following specific activities for GAST-D site acceptance should be conducted.

6.6.2.1 Verification of site-specific parameters

The following broadcast GAST-D signal-in-space integrity parameters should be determined for the site:

- Ground pseudorange uncertainty σpr_gnd_D and σpr_gnd_30: preliminary values determined during design qualification should be confirmed as valid for the site
- Residual ionospheric uncertainty $\sigma vert\_iono\_gradient\_D$: determined by an analysis of regional ionospheric statistics

In addition, supplementary or new monitors limits that are valid for GAST-D must be determined and validated.

6.6.2.2 Ground testing

The following list indicates the ground tests that should be conducted during site acceptance:

- Pseudorange domain accuracy evaluation (GAD Assessment)
- Evaluation of error correlation between RRs, estimation of the distribution of the errors.
- Position domain accuracy functional test (GAST-D 100s and 30s position solution)
- Continuity of Service performance demonstration of the installed equipment
- Data broadcast parameters content verification; Type 11, Type 2 ADB3 and ADB4 message content
- VDB runway surface coverage

6.6.2.3 Flight testing

For GAST-D, no specific flight testing for site acceptance is envisaged.

7 Siting and GS architecture requirements

The requirements for the 15.3.6 project are listed in a requirements matrix in D03. In this document, we have focused on what we anticipate should be the requirements for ground architecture and airport installation for a GAST D system, where it differs from a GAST C installation. These have been extracted, but it should be noted that 1) we do not, at this point in time, have any practical experience with GAST D installations, and 2) these requirements are not part of any standard and should therefore be considered more as suggestions for standardisation, and conditioned by positive results concerning both feasibility and quality. Note that some of the items below are part of the baseline development SARPS [8]. Also, there are a few aspects which are especially important for GAST D due to increased performance requirements, but should also be considered for GAST C. (e.g requirements related to RFI and mask angles)

In the text, there is a distinction between the word “shall” and “should”, where “shall” indicates that the requirement is mandatory, whereas “should” is to be considered as a recommendation.

The draft requirements identified in this study are as follows:

- [Performance1]: The minimum number of installed antennas/receivers for a GAST D GS shall be four. (See chapter 2.2).
- [Iono1]: Maximum distance from GBAS reference point to any threshold served by the station shall be 5km. (See chapter 4.1).
- [Availability1]: GNSS RRA sites should be such that the base of the antenna has a clear horizon above 3° elevation at all azimuths. (See chapter 4.2.2).
- [Integrity1]: Antenna height shall be determined on the basis of generic multipath considerations, nearby objects, vegetation, snow/water conditions, risk of jamming and on-site activities such as grass mowing. (See chapter 4.2.2).
- [Performance2]: It should be considered to add suspension to the antenna in case of excessive vibrations. It should be noted that suspension cords may affect the antenna performance. (See chapter 4.2.2).
- [Iono 2]: Antenna separations shall be determined based on risk of correlated multipath, and the selected Ionospheric gradient monitoring scheme. (See chapter 4.2.5).
- [Iono3]: Depending on selected ionospheric gradient monitoring scheme, the effective baselines shall be perpendicular to the worst-case wave front and thus aligned with the runway for which GAST D operation shall be performed. (See chapter 5.7.2.1.2.1).
- [Iono4]: The stability of the antenna foundation should be considered with respect to the selected ionospheric gradient monitoring scheme. (See chapter 6.4.2.1).
- [Coverage1]: Unobstructed line-of-sight should exist from the antenna to all operational areas, including runways for roll-out. Minor fixed structures and traffic may be allowed in the line of sight. (See chapter 4.3.2).
- [Interference1]: GS architecture should take the risk of interference into account such that the GS is robust against interference on a limited number of receivers. (See chapter 5.2.2.1).
- [Interference2]: GS site selection should take the risk of jamming into account, i.e. antennas should be sited at as far as possible from public areas such as roads. (See chapter 5.2.2.1).
- [Performance3]: The receiver technology (correlators and filters) should be such that the effect of multipath is limited. (See chapter 5.3.2).

- [Performance4]: A multipath assessment technique based on Code-minus-carrier (CMC) shall be used to determine the performance characteristics of the site. (See chapter 5.3.3.2).

- [Iono5]: Depending on ionospheric conditions, the risk of exposure to scintillations should be taken into account in the monitor design. (See chapter 2.2).

8 Conclusions

In this document, we have presented the challenges connected to siting and airport installation for a GAST D GBAS ground station. Even though the authors have been focused on highlighting the new challenges introduced by GAST D, as compared to GAST C, the distinction has not always been so easy to make, as many of the requirements are common.

The main points identified in this task, have been highlighted and presented as draft requirements in chapter 7, Siting and GS architecture Requirements.

During the final phases of 15.3.6, we expect to gain more detailed knowledge based on the siting and validation work. This is expected to have some impact on the siting requirements. The requirements where an impact can be expected are the following:

- [Iono4]: Long term stability of antenna (See chapter 6.4.2.1)
- [Coverage1]: Unobstructed line-of-sight. More details, especially regarding moving objects/traffic, may possibly become available (See chapter 4.3.2).

Such changes, or additional details, will be addressed in the Task 19.

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Appendix A Obstacle Limitation Surfaces for Precision Approach runways category II / III

ICAO Annex 14 requirements for obstacle limitation surfaces are specified on the basis of the intended use of a runway, i.e. take-off or landing and type of approach, and are intended to be applied when such use is made of the runway.

Obstacle limitation surfaces are specified in ICAO Annex 14 and quoted below. Applicable obstacle limitation surfaces for precision approach runways category II / III are highlighted in the table below with red dashed rectangles. Further guidance is given in the Airport Services Manual (Doc 9137), Part 6.

- The following obstacle limitation surfaces shall be established for a precision approach runway category II or III:
  - —conical surface;
  - —inner horizontal surface;
  - —approach surface and inner approach surface;
  - —transitional surfaces;
  - —inner transitional surfaces; and
  - —balked landing surface.
- The heights and slopes of the surfaces shall not be greater than, and their other dimensions not less than, those specified in the table below, except in the case of the horizontal section of the approach surface.
- The approach surface shall be horizontal beyond the point at which the 2.5 per cent slope intersects:
  - —a horizontal plane 150 m above the threshold elevation; or
  - —the horizontal plane passing through the top of any object that governs the obstacle clearance limit;

  whichever is the higher.
- Fixed objects shall not be permitted above the inner approach surface, the inner transitional surface or the balked landing surface, except for frangible objects which because of their function must be located on the strip. Mobile objects shall not be permitted above these surfaces during the use of the runway for landing.
- New objects or extensions of existing objects shall not be permitted above an approach surface or a transitional surface except when, in the opinion of the appropriate authority, the new object or extension would be shielded by an existing immovable object.
  - —Note.— Circumstances in which the shielding principle may reasonably be applied are described in the Airport Services Manual (Doc 9137), Part 6.
- Recommendation.
  - —New objects or extensions of existing objects should not be permitted above the conical surface and the inner horizontal surface except when, in the opinion of the appropriate authority, an object would be shielded by an existing immovable object, or after aeronautical study it is determined that the object would not adversely affect the safety or significantly affect the regularity of operations of aeroplanes.
  - —Existing objects above an approach surface, a transitional surface, the conical surface and inner horizontal surface should as far as practicable be removed except when, in the opinion of the appropriate authority, an object is shielded by an existing immovable object, or after aeronautical study it is determined that the object would not

adversely affect the safety or significantly affect the regularity of operations of aeroplanes.

▪Note.— Because of transverse or longitudinal slopes on a strip, in certain cases the inner edge or portions of the inner edge of the approach surface may be below the corresponding elevation of the strip. It is not intended that the strip be graded to conform with the inner edge of the approach surface, nor is it intended that terrain or objects which are above the approach surface beyond the end of the strip, but below the level of the strip, be removed unless it is considered they may endanger aeroplanes.

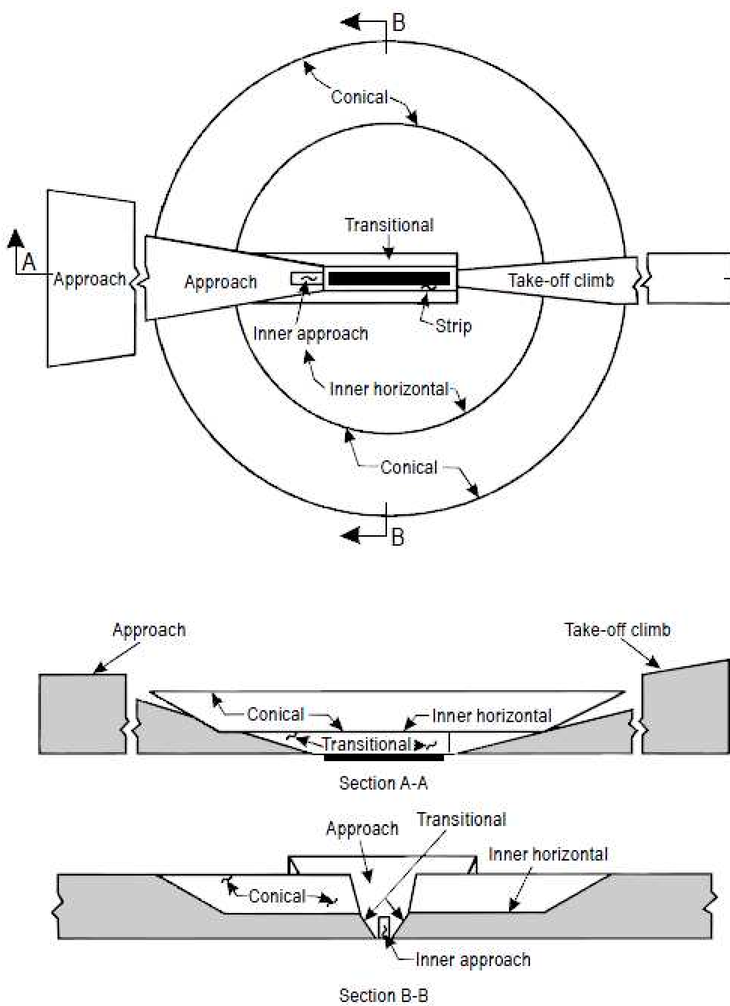

Figure 9-1: Obstacle Limitation Surfaces

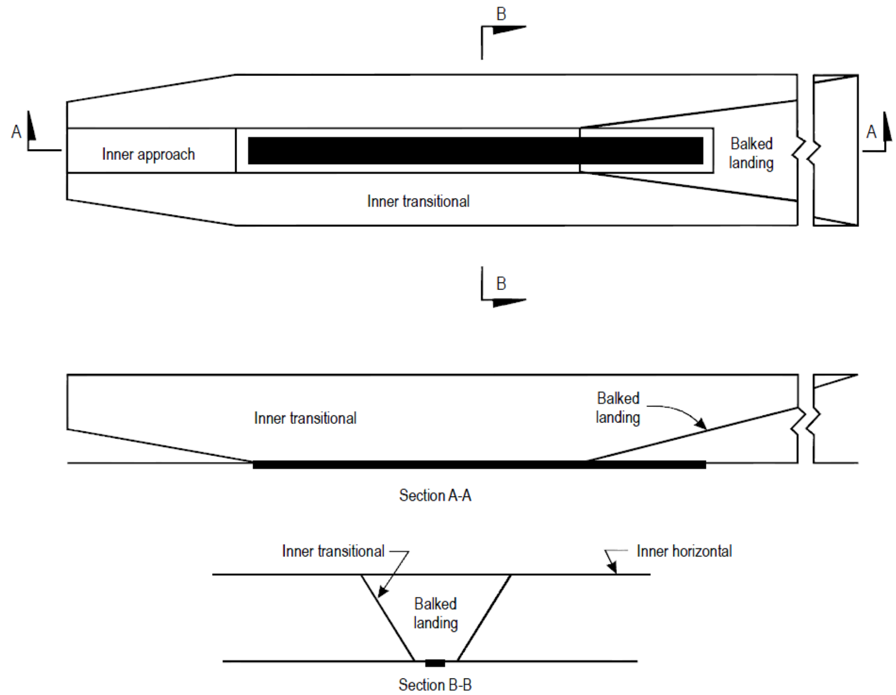

Figure 9-2: Inner approach, inner transitional and balked landing obstacle limitation surfaces

APPROACH RUNWAYS

Surface and dimensions[a] (1)	Non-instrument Code number 1 (2)	2 (3)	3 (4)	4 (5)	Non-precision approach Code number 1,2 (6)	3 (7)	4 (8)	Precision approach category I Code number 1,2 (9)	3,4 (10)	II or III Code number 3,4 (11)
CONICAL										
Slope	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Height	35 m	55 m	75 m	100 m	60 m	75 m	100 m	60 m	100 m	100 m
INNER HORIZONTAL										
Height	45 m	45 m	45 m	45 m	45 m	45 m	45 m	45 m	45 m	45 m
Radius	2 000 m	2 500 m	4 000 m	4 000 m	3 500 m	4 000 m	4 000 m	3 500 m	4 000 m	4 000 m
INNER APPROACH										
Width	—	—	—	—	—	—	—	90 m	120 m[e]	120 m[e]
Distance from threshold	—	—	—	—	—	—	—	60 m	60 m	60 m
Length	—	—	—	—	—	—	—	900 m	900 m	900 m
Slope								2.5%	2%	2%
APPROACH										
Length of inner edge	60 m	80 m	150 m	150 m	150 m	300 m	300 m	150 m	300 m	300 m
Distance from threshold	30 m	60 m	60 m	60 m	60 m	60 m	60 m	60 m	60 m	60 m
Divergence (each side)	10%	10%	10%	10%	15%	15%	15%	15%	15%	15%
First section										
Length	1 600 m	2 500 m	3 000 m	3 000 m	2 500 m	3 000 m	3 000 m	3 000 m	3 000 m	3 000 m
Slope	5%	4%	3.33%	2.5%	3.33%	2%	2%	2.5%	2%	2%
Second section										
Length	—	—	—	—	—	3 600 m[b]	3 600 mb	12 000 m	3 600 m[b]	3 600 m
Slope	—	—	—	—	—	2.5%	2.5%	3%	2.5%	2.5%
Horizontal section										
Length	—	—	—	—	—	8 400 m[b]	8 400 m[b]	—	8 400 m[b]	8 400 m
Total length	—	—	—	—	—	15 000 m	15 000 m	15 000 m	15 000 m	15 000 m
TRANSITIONAL										
Slope	20%	20%	14.3%	14.3%	20%	14.3%	14.3%	14.3%	14.3%	14.3%
INNER TRANSITIONAL										
Slope	—	—	—	—	—	—	—	40%	33.3%	33.3%
BALKED LANDING SURFACE										
Length of inner edge	—	—	—	—	—	—	—	90 m	120 m[e]	120 m[e]
Distance from threshold	—	—	—	—	—	—	—	c	1 800 m[d]	1 800 m
Divergence (each side)	—	—	—	—	—	—	—	10%	10%	10%
Slope	—	—	—	—	—	—	—	4%	3.33%	3.33%

a. All dimensions are measured horizontally unless specified otherwise.
b. Variable length (see 4.2.9 or 4.2.17).
c. Distance to the end of strip.
d. Or end of runway whichever is less.
e. Where the code letter is F (Column (3) of Table 1-1), the width is increased to 155 m. For information on code letter F aeroplanes equipped with digital avionics that provide steering commands to maintain an established track during the go-around manoeuvre, see Circular 301 — *New Larger Aeroplanes — Infringement of the Obstacle Free Zone: Operational Measures and Aeronautical Study*.

Figure 9-3: Dimensions and slopes of obstacle limitation surfaces – Approach runways

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