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Fly by Data Link: Feasibility of a Relative Navigation Solution for Aviation Relying on a Future L-Band Data Link

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ABSTRACT

The main purpose of this work is to study an alternative solution for aeronautical aircraft navigation contributing to the rationalization of the existing European ground navigation infrastructure.

The emerging Performance Based Navigation (PBN) concept, described in the document 9613 of the International Civil Aviation Organization (ICAO), calls for increased reliance on Global Navigation Satellite Systems (GNSS) (and its augmentation/differential correction systems[1]) but retaining ground beacons such as the Distance Measuring Equipments (DME) to cope with Global Positioning System (GPS) and GALILEO outages (e.g. jamming/solar storms).

The present work will focus on demonstrating the feasibility of an alternative technology to allow the decommissioning of such DME beacons based on the re-use of future L-Band Air Ground Data Link (LDACS) communication solutions being subject of research studies. Such data links may support the required levels of positioning, navigation and timing required to complement GNSS when the aircraft fly in an area navigation environment.

This work will describe the LDACS data link technologies[2] and will explain how such communications enablers would be able to support a "relative navigation" function similar to the one available in military data link technologies using a geodetic grid.

The feasibility of the proposed solution will be demonstrated on the basis of lessons learnt from military relative navigation and simulations which will evidence the technical performance/error parameters of the system in terms of ranging, bearing and horizontal positioning and other relevant QoS aspects. In addition, the multipath and co-site interference effects will be also discussed.

Should the proposed solution be demonstrated as viable, it may open the door, not only for synergies leading to a more seamless aircraft equipage but also to the rationalization of aeronautical systems in the spectrum band 960-1215 MHz, which is highly congested and subject of stringent non-interference basis operational limitations.

Keywords

Air Traffic, Aeronautical Navigation, Air-Ground Data Link, L-Band Spectrum, Satellite Navigation, Relative Navigation, Distance Measuring Equipment (DME), Ranging, Time

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[1] Ground Based, Aircraft Based and Space Based Augmentation System (GBAS, ABAS, SBAS)
[2] based on Orthogonal Frequency Division Multiplex (OFDM)/Time Division Multiple Access (TDMA)

Difference Of Arrival, Satellite Outages, OFDM technology, Kalman Filter.

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RESUMO

O presente trabalho estuda uma solução alternativa de navegação aeronáutica que contribua para a racionalização da infrastrutura terrestre de ajudas-rádio de navegação na Europa.

O conceito designado de “Performance Based Navigation (PBN)” emerge actualmente ao nível da Organização Internacional de Aviação Civil, visando o aperfeiçoamento do sistema de gestão do tráfego aéreo ao nível da eficiência, segurança e capacidade.

O conceito PBN promove a modernização da infrastrutura aeronáutica com base na utilização preferencial de sistemas de navegação por satélite, designadamente mediante o recurso a sinais disponibilizados pelas constelações “Global Navigation Satellite System (GNSS)”. Face às vulnerabilidades dos sistemas GNSS a interferências RF, “jamming” deliberado ou fenómenos solares, foi decidido manter uma infrastrutura de recurso/”backup”, para mitigar falhas GNSS, baseada numa rede de rádio-ajudas terrestres “Distance Measuring Equipment (DME)”.

Visto que estes DMEs não facultam uma boa cobertura, especialmente a baixa altitude, e tratando-se de equipamentos próximos da obsolescência tecnológica e pouco eficientes em termos de espectro rádioeléctrico, a sua racionalização requer uma tecnologia alternativa.

O presente trabalho explora o recurso a novas tecnologias aeronáuticas de comunicações dados ar-solo, designadamente o futuro “data link” OFDM/TDMA de banda L (LDACS), verificando a sua adequação para suportarem as funções de navegação descritas substituindo os DMEs. Pretende-se confirmar a viabilidade com base no conceito de Navegação Relativa (RELNAV) usado em contexto militar recorrendo a filtros Kalman.

As características da tecnologia LDACS são descritas e são apresentados resultados de testes do seu desempenho em termos de medição de distâncias (“ranging”). Com base nas capacidades RELNAV militares são propostos melhoramentos baseados em filtros Kalman, simulando para demonstrar que o LDACS pode ser usado para função de navegação.

Demonstrada a viabilidade, fica em aberto a oportunidade para sinergias que poderão viabilizar a racionalização da infrastrutura terrestre de navegação e aviónicos.

Palavras-chave

Tráfego Aéreo, Navegação Aeronáutica, Comunicações, “Data Link”, Espectro na Banda L, Navegação por Satélite, “Global Navigation Satellite System” (GNSS), Navegação Relativa, “Distance Measuring Equipment” (DME), Distância, OFDM, Filtro Kalman.

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ACRONYM LIST

A/A	Air-Air
ABAS	Aircraft-Based Augmentation System
ACARS	Aircraft Communication and Reporting System
ACL	ATC Clearance
ACM	ATC Communications Management
ADF	Automatic Direction Finder
ADS	Automatic Dependent Surveillance (C - Contract, B – Broadcast)
AeroMACS	Aeronautical Mobile Airport Communications System
AFCS	Automatic Flight Control System
A/G	Air-Ground
AIS	Aeronautical Information Services
AMC	ATC Microphone Check
ANSP	Air Navigation Service Provider
AOA	ACARS over AVLC
AOC	Airline Operational Communications
APC	Airline Passenger Communications
A-PNT	Alternative Positioning Navigation and Timing
APV	Approach Procedure with Vertical Guidance
AS	Airborne Statiom
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network (ICAO concept)
ATS	Air Traffic Services
AVLC	Aviation VHF Link Control
Baro VNAV	Barometric Vertical Navigation
BER	Bit Error Rate
BLOS	Beyond Line Of Sight
B-RNAV	Basic RNAV (RNP 5)
C2	Command and Control
CCC	Common Communications Channel
CDMA	Code Division Multiple Access
CNS	Communications, Navigation and Surveillance
COM	Communications
CP	Cyclic Prefix
CPDLC	Controller-Pilot Data Link Communications

CSMA	Carrier Sense Multiple Access
DAB	Digital Audio Broadcast
DAP	Downlink Airborne Parameters
D-ATIS	Data Link ATIS
DCL	Departure Clearance
DLIC	Data Link Initiation Capability
DLR	Deutsches Zentrum fur Luft- und Raumfahrt
DME	Distance Measuring Equipment
DVB	Digital Video Broadcast
DVOR	Doppler VOR
EASA	European Aviation Safety Agency
EATMN	European Air Traffic Management Network
ECAC	European Civil Aviation Conference
EGNOS	European Geostationary Navigation Overlay Service
EUROCAE	European Organisation for Civil Aviation Equipment
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FCI	Future Communications Infrastructure
FCS	Future Communications Study
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FL	Forward Link
FMS	Flight Management System
FPL	Flight Plan
FRS	Future Radio System
FTE	Flight Technical Error
GAT	General Air Traffic
GBAS	Ground-Based Augmentation System
GEOGRID	Geodetic Grid
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Ground Station
GSM	Global System for Mobile
ICAO	International Civil Aviation Organisation
ICI	Inter Carrier Interference
IFP	Instrument Flight Procedures
ILS	Instrument Landing System
INS	Inertial Navigation System

IP	Internet Protocol
IPS	Internet Protocol Suite
ISI	Inter Symbol Interference
ISO	International Standardisation Organisation
ITU	International Telecommunications Union
JTIDS/MIDS	Joint Tactical Information Distribution System/Multifunctional Information Distribution System
LAN	Local Area Network
LDACS	L-Band Digital ATM Communications System
LMM	Locator Middle Marker
LOM	Locator Outer Marker
LoS	Line of Sight (NLOS – Non-Line of Sight)
LQE	Linear Quadratic Estimation
MAC	Media Access Control
MCDU	Multipurpose Control Display Unit
MEO	Medium Earth Orbit
MLS	Microwave Landing System
MM	Middle Marker
MMSE	Minimum Mean Square Error
MOPS	Minimum Operation[al] Performance Specifications
MOR	Military Operational Requirement
NATO	North Atlantic Treaty Organisation
NAVAIDS	Navigation Aids
NC	Navigation Controller
NDB	Non-Directional Beacon
NM	Nautical Miles
NSE	Navigation System Error
OFDM	Orthogonal Frequency Division Multiplexing
OM	Outer Marker
OPMA	On-Board Performance Monitoring and Failure Alerting
OS	(GALILEO) Open Service
OSI	Open Systems Interconnection
PBN	Performance Based Navigation
PDE	Path Definition Error
PPS	Precise Positioning Service
PPLI	Precise Participant Location Information
PRS	(GALILEO) Public Regulated Service
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying

QoS	Quality of Service
Q_p	Position Quality
RAIM	Receiver Autonomous Integrity Monitoring
Rb	Rubidium
RELGRID	Relative Grid
RELNAV	Relative Navigation
RL	Reverse Link
RL RA	Reverse Link Random Access
RMSE	Root Mean Squared Error
RNAV	Area Navigation (or Random Navigation)
RNP	Required Navigation Performance
SARPS	Standards and Recommended Practices (ICAO)
SATCOM	Satellite Communications
SBAS	Space-Based Augmentation System
SES	Single European Sky
SESAR	Single European Sky ATM Research
SNR	Signal Noise Rate
SoL	(GALILEO) Safety of Life
SSR	Secondary Surveillance Radar
STANAG	Standardisation Agreement
TACAN	(UHF) Tactical Air Navigation Aid
TDMA	Time Division Multiple Access
TDD	Time Division Duplex
TDOA	Time Difference Of Arrival
TGL	Temporary Guidance Leaflet
TMA	Terminal Area
TOA	Time of Arrival
TSE	Total System Error
UAT	Universal Asynchronous Transceiver
UHF	Ultra High Frequency
VDL	VHF Data Link
VHF	Very High Frequency
VOR	VHF Omnidirectional Radio Range
VORTAC	VOR associated with TACAN for civil usage
WAM	Wide Area Multilateration
WIMAX	Worldwide Interoperability for Microwave Access
WRC	World Radiocommunication Conference

1 INTRODUCTION

1.1 CONTEXT

Presently, European airspace accommodates around 30.000 flights a day. Long-term air transport traffic forecast for Europe, in terms of scheduled flights, predict 14.4 million flights in 2035, 50% more than in 2012. Those flights rely on the European Air Traffic Management Network (EATMN) infrastructure, which needs modernization to cope with the predicted growth in air traffic and its increased complexity as well as to pursue safety, cost-saving and environmental objectives.

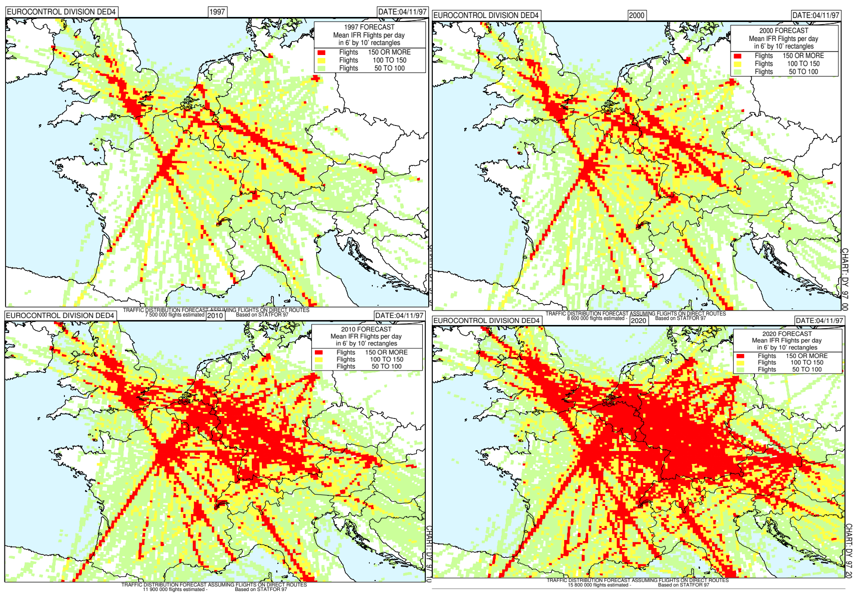


Figure 1 – Evolution of European Air Traffic from 1997 to 2020
(Source EUROCONTROL)

Such modernization efforts are ongoing in the context of the Single European Sky ATM Research (SESAR) Work Programme (www.sesarju.eu), founded by the European Commission and EUROCONTROL[3], in partnership with the European industry. Current Research and Development (R&D) covers the deployment of IP-based network centric information structures, satellite-based navigation, Air Traffic Control (ATC) automation and increased data connectivity between aircraft and ground systems.

In several European countries, air-ground data communication[4] services are already

[3] European Organisation for the Safety of Air Navigation
[4] Designated as "data links" in the aeronautical terminology

operational. This infrastructure is under implementation to support Controller-Pilot Data Link Communications (CPDLC), replacing voice exchanges between the cockpit and ground ATC, using short messages to support routine communications. CPDLC applications include the initiation of the communications service, ATC clearances (departure, climb and descent), management of repetitive frequency changes and microphone check.

The technology of choice for CPDLC is compliant with the Aeronautical Telecommunications Network (ATN)[5] concept of the International Civil Aviation Organisation (ICAO) in the upper part of the ICAO VHF aeronautical communications spectrum band (118 MHz to 138 MHz), using the VHF Digital Link Mode 2 (VDL2) radio system. The implementation of this service in Europe was subject of Single European Sky (SES) regulatory measures with ground implementation and aircraft equipage mandated by the European Commission (EC) Regulation 29/2009 of 16 January 2009 on Data Link Services [1].

This initial development will be only the first step for the introduction of more advanced air-ground data link technologies, designated as Future Communications Infrastructure (FCI) [2]. FCI is designed to sustain more demanding requirements.

FCI comprises three segments: a satellite-based data link system (SATCOM) for the oceanic, remote and continental environments, an airport surface data link system, referred to as the Aeronautical Mobile Airport Communications System (AeroMACS), and a terrestrial data link system for continental airspace, referred to as the L-band Digital Aeronautical Communications System (LDACS).

Aeronautical navigation is another fundamental aviation enabler. There is a need to determine aircraft´s position, and to receive information that allows the pilot to steer and guide the aircraft along the route to be flown.

Today, air transport operations rely on Navigation Aids (NAVAIDS) for position-determination and to obtain ranging and bearing indications. On board, aircraft avionics are able to calculate the aircraft's position from the information received from those NAVAIDS.

The traditional ground-based NAVAID infrastructure [3] comprises: Non-Directional Beacon (NDB), Very High Frequency Omnidirectional Ranging systems (VOR) and Distance Measuring Equipment (DME). Today's infrastructure includes also satellite constellations: U.S. Global Positioning System (GPS), European GALILEO and the Russian GLONASS. The

[5] described in Annex 10 to the ICAO Convention / Open Systems Interconnection

generic name for any satellite constellation used for positioning is Global Navigation Satellite System (GNSS).

The introduction of GNSS raises the opportunity to rationalise the ageing ground-based systems (e.g. NDB, DME and VOR). However, reliance of navigation being placed upon signals from a satellite source, as the sole means, raises complex safety challenges: in fact, the GNSS signals can be lost due to jamming or natural interference (e.g solar storm). Consequently, there is a need to retain a fall back/back up terrestrial infrastructure, presently based on DME, together with autonomous onboard navigation functions, like Inertial Navigation Systems (INS), to mitigate GNSS outages and to ensure continued operations.

DME technology is now close to obsolescence and does not ensure adequate coverage to support more advanced navigation concepts, e.g. multitrack Area Navigation / Random Navigation (RNAV). It is also impacted by spectrum constraints in the band 960 MHz to 1215 MHz. Due to the previous reasons and also to facilitate the rationalization of aircraft equipage, it is imperative to introduce Alternative Positioning Navigation and Timing (A-PNT) technologies. The use of "pseudolites", reutilization of surveillance equipment, for example Secondary Surveillance Radar (SSR) Mode S, or reliance on data links to exchange ranging and bearing / positioning information are amongst the A-PNT candidates to support such aeronautical navigation functions and enable the gradual decommissioning of current VORs and DMEs.

The present thesis discusses the feasibility of using the air-ground data link as A-PNT option taking advantage of the emergence of the Future Communications Infrastructure (FCI)[6] concept and further development of LDACS technology. Reference is also made to military data links used today to sustain similar Relative Navigation (RELNAV) functions.

1.2 OBJECTIVE AND SCOPE

The main objective of this academic work is to discuss and describe an alternative solution for aeronautical aircraft navigation based on the use of new data link technologies as a means of A-PNT. This navigation solution shall contribute to the rationalization of the existing European ground navigation infrastructure.

This work intends to demonstrate the feasibility of Future COM terrestrial data link, LDACS, to replace DMEs in providing ranging and positioning information for aircraft navigation.

[6] Also known as "Future COM"

A very important disclaimer is that the present thesis does not intend to discuss at length the Orthogonal Frequency Division Multiplexing (OFDM) transmission technique and the methodologies to address multipath, inter symbol and inter carrier interference. However, a brief evaluation of the level of multipath mitigation/coherent detection improvements offered by channel estimation is swiftly introduced based on some simulations to illustrate that feasibility could be attained with the use of Kalman filters.

This document fulfils academic purposes. It shall not support directly any technical implementation purposes. Additional standardisation or industrialisation activities would be required. It references only information openly available and considered unclassified/non-sensitive and not subject of any industrial copyright.

Intended readership comprises academic context and participants in aviation research activities in telecommunications engineering and aeronautical technologies. The author developed this work on private grounds without any link to any of his professional commitments within EUROCONTROL.

1.3 DOCUMENT STRUCTURE

This document includes:

- **Introduction** – Setting the scene, providing background information and describing the air transport and technological context.
- **The Need for Alternative Positioning Navigation and Timing** – Presenting future navigation concepts and the justification for the introduction of different technology solutions for navigation enabling the replacement of present ground-based NAVAIDs. Distance Measuring Equipment technology is described.
- **Air-Ground Data Link Technologies** – Describing existing and future air-ground data communications technologies with a particular focus on the LDACS data link.
- **Relative Navigation** – Presenting the objectives of RELNAV and describing the current use of military data links to sustain RELNAV functions.
- **Feasibility Assessment and Simulations** – Recalling known results from previous trials and specific simulations to validate improvements to the candidate A-PNT, the LDACS OFDM data link, against the identified performance targets in terms of ranging accuracy and position-determination.
- **Conclusion –** Summary of key findings, recommendations and opportunities.

2 AERONAUTICAL NAVIGATION INFRASTRUCTURE

2.1 TERRESTRIAL NAVIGATION INFRASTRUCTURE

Knowing an aircraft's position in real time it is a fundamental element of aeronautical navigation. Today, most aircraft have highly sophisticated integrated modular avionics using position information from a variety of navigation sources (NAVAIDS), terrestrial or space-based, to calculate the steering signals and autopilots to ensure that the aircraft follows the desired track.

The traditional ground-based navigation infrastructure consists of NAVAIDS, introduced more than 50 years ago, such as:

- Non Directional Beacon (NDB),
- Very High Frequency Omni-Directional Ranging Systems (VOR),
- Distance Measuring Equipment (DME),
- Tactical Air Navigation (TACAN) Equipment (for the military).

NDBs are low frequency radio transmitters of omni-directional signals used as an instrument approach for airports and offshore platforms. NDBs are designated as Locator when used as a replacement at a location where normally a 75 MHz Marker would be used as Middle Marker (MM) or Outer Marker (OM) for Instrument Landing System (ILS), co-located with or used instead of a 75 MHz marker beacon as part of an ILS-system. NDBs are currently planned for gradual phase out.

VORs provide bearing information and are also planned for gradual decommissioning (with the exception of a residual number required to support an advanced navigation specification designated as RNAV-5) [4]. DME is often "paired" with VOR, ILS or Microwave Landing System (MLS). When the pilot or flight computer selects the required VOR, ILS frequency or MLS channel the corresponding DME channel is automatically selected.

VOR and DME/N or DME/P[7] are ICAO radio-navigation systems that can be operated independently or collocated (paired). VORs operate in the band 108 MHz to 111.975 MHz and are susceptible to multipath interference from surrounding terrain, buildings, trees and power lines. Consequently, when necessary, a replacement can be a Doppler VOR (DVOR) transmitter, more resistant to multipath interference than the conventional one.

DME /N or DME /P provide for continuous and accurate indications in the cockpit (interrogator) of the slant range distance from the ground (transponder) reference point to the aircraft's DME interrogator. DME /N or DME /P operate in the band 960 MHz to 1215 MHz and are vulnerable to multipath effects; impacting both transponder and interrogator. Later in this thesis, more details are included on the characteristics of DME.

TACAN is a radio-navigation system (960 MHz to 1215 MHz) considered the military equivalent of civil VOR/DME that provides a pilot with the slant-range distance information, like any DME, as well as optional azimuth (bearing) information, similar to a VOR. Many TACANs are operated, or even owned, by civil air traffic service providers, providing to civil and military aircraft azimuth and slant range distance information at appropriate locations. Aircraft equipped with DME /N or DME /P interrogator may use a TACAN as DME substitute. When TACAN is collocated with civil VOR stations it is designated VORTAC.

2.2 GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

Today's infrastructure supporting aeronautical navigation includes also the use of satellite constellations comprising the U.S. Global Positioning System (GPS) / NAVSTAR, Russian GLONASS and the European GALILEO, currently being deployed, and a number of augmentation services which complement/correct signals-in-space. The generic designation for the satellite constellations used for aviation is Global Navigation Satellite System (GNSS) [5].

GNSS is a worldwide position and time determination system, which includes the abovementioned satellite constellations, to be operated through aircraft receivers (gradually multiconstellation/multifrequency), and system integrity monitoring, augmented as necessary to support advanced area navigation concepts.

- The GPS space segment is composed of twenty four satellites in six orbital planes. The satellites operate near-circular 20.200 km (10.900 NM) orbits at

[7] Distinction is made between DME /P - the distance measuring element of the MLS and DME /N - distance measuring equipment, primarily serving operational needs of en-route or TMA navigation.

an inclination angle of 55 degrees to the equator, and each satellite completes an orbit in approximately 12 hours. The GLONASS space segment consists of twenty-four operational satellites and several spares.

- GLONASS satellites orbit at an altitude of 19.100 km with an orbital period of 11 hours and 15 minutes. Eight evenly spaced satellites are arranged in each of the three orbital planes, inclined 64.8 degrees and spaced 120 degrees apart.

- GALILEO constellation (still being deployed) when fully operational, will comprise 30 satellites in Medium Earth Orbit (MEO) at an altitude of 23.222 km. The satellites will occupy each of three orbital planes inclined at an angle of 56° to the equator. The satellites will be spread evenly around each plane and will take about 14 hours to orbit the Earth.

  Different levels of performance can be identified for each Galileo service. For the GALILEO Open Service (OS) there are no particular integrity requirements. The performances for horizontal positioning accuracy at 95% for a dual-frequency receiver are 4 m for horizontal accuracy and 8 m for vertical accuracy with a service availability of 99%.

  For the GALILEO Safety of Life (SoL) and the GALILEO Public Regulated Service (PRS), the performance requirements include stringent horizontal and vertical accuracy, integrity, continuity and time to alert for different service levels. The availability of the service should be 99.5% for both services.

GALILEO plans to be interoperable with other GNSS constellations. Users should be able to receive position data with the same receiver from any of the satellites in any combination. By offering dual frequencies as standard, GALILEO will deliver real-time positioning accuracy down to the meter range. The combination of GALILEO and GPS signals in dual receivers will open the door to new GNSS applications that require a higher level of precision than currently available with GPS alone. From most locations, six to eight GALILEO satellites will be visible which, in combination with GPS signals, will allow positions to be determined up to within a few centimetres.

In conclusion, the present aviation policy on GNSS envisages a gradual reliance on satellite navigation towards its possible use as a sole navigation service. For that it needs to be proven as the most cost beneficial solution and that safety and security requirements are met. We will see later on that, for the moment, the risk of GNSS outages still requires the retention of backup terrestrial NAVAIDS. The vision for implementing this policy is based on the combined use of signals coming from, at least, two constellations, each with diverse radio frequencies. User receivers will process signals from different GNSS constellations in combination with the so-called augmentations, which correct the original satellite signals (differential correction). GNSS will be a fundamental enabler for the advanced navigation concepts promoted by ICAO under the framework of the Performance Based Navigation (PBN) concept.

The original design of satellite constellations did not aim at meeting aviation safety requirements alone. Therefore, augmentation systems have been developed to meet this need, providing integrity, improved accuracy and continuity. These augmentation systems either reside on the aircraft, known as Aircraft Based Augmentation System (ABAS), or are based on specifically deployed infrastructure. The European Geostationary Navigation Overlay Service (EGNOS) provides continent-wide Space Based Augmentation System (SBAS) and Ground Based Augmentation System (GBAS) supports precision approach.

2.3 ADVANCED CONCEPTS: PERFORMANCE BASED NAVIGATION (PBN)

Already some decades ago, Area Navigation (also known as Random Navigation - RNAV) [6] systems started to be introduced in aircraft avionics suites. RNAV uses signals from multiple navigation aids to compute the position enabling aircraft to navigate along any desired route independent from the location of the ground navigation aids. This separation of the route structure from the location of navigation aids allowed new routes to be implemented without new aids having to be installed.

RNAV definition describes it as a method, which permits aircraft navigation along any desired flight path within the coverage of the associated navigation aids or within the limits of the capability of self-contained aids [7], or a combination of these methods. RNAV equipment includes any equipment that operates by automatically determining aircraft position from one or a combination of sensors with the means to establish and follow a desired path. After the designation RNAV it is normally added a figure identifying the lateral navigation performance in nautical miles for 95% of the time (e.g. the specification RNAV-1 represents the ability to fly with 1NM of lateral navigation performance 95% of the time), see Figure 2.

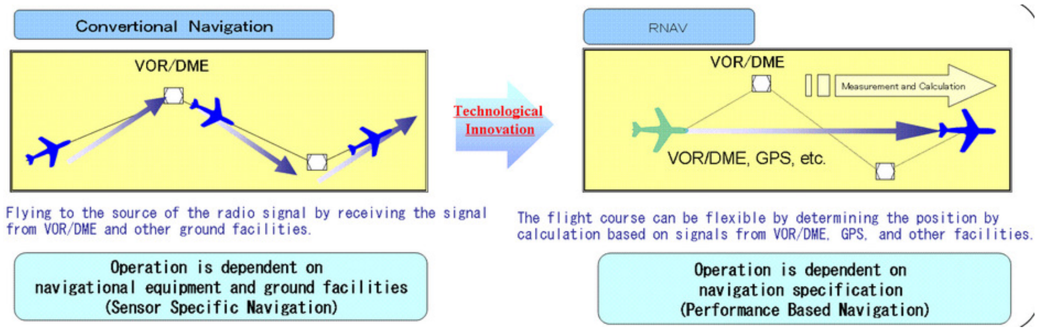


Figure 2 – From Sensor Specific to Performance Based Navigation (PBN)
(Source www.mlit.go.jp)

The wide implementation of area navigation specifications, and associated functionalities, is being strongly promoted by ICAO and other Organisations under the concept of Performance Based Navigation (PBN), defined in the ICAO document 9613 (PBN Manual) [8]. PBN enables new airspace structures (e.g. tighter spacing between Air Traffic Service (ATS) routes, continuous descent/climb operations, etc.) leading to improvements in terms of safety, efficiency and capacity and enabling better access to airspace and airports while mitigating aviation's impact on the environment [9]. European regulatory initiatives on PBN are presently ongoing to accelerate deployment.

PBN represents a fundamental shift from sensor-based to performance-based navigation. The PBN concept has expanded area navigation techniques, originally centred upon lateral navigation accuracy only, to a more extensive statement of required performance related to accuracy, integrity and continuity along with how this performance is to be achieved in terms of aircraft and crew requirements, see Figure 3.

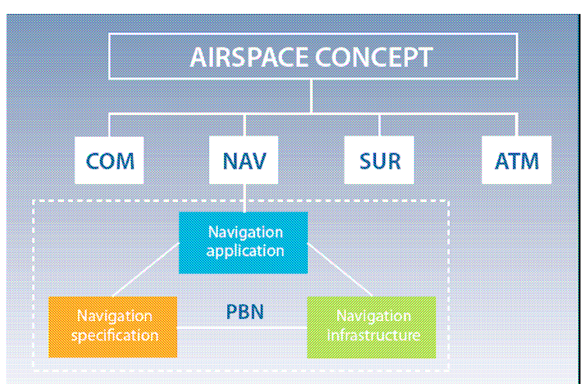


Figure 3 – Performance Based Navigation (PBN) Concept
(Source EUROCONTROL)

The objectives of PBN were to ensure global interoperability through the standardisation of RNAV and Required Navigation Performance (RNP) system performance through internationally agreed RNAV and RNP specifications and to limit the proliferation of navigation specifications in use worldwide.

To support any airspace concept, along with Communications, Surveillance and ATM, PBN relies in a three-component combination: A navigation application shall consist in the implementation of a navigation specification and associated supporting navigation infrastructure, applied to routes, procedures, and/or defined airspace volumes.

Navigation Application reflects the ATS routes and Instrument Flight Procedures (IFP) based on the NAVAID Infrastructure and Navigation Specification.

Navigation Specification is a technical and operational specification that identifies the required functionality of the onboard area navigation equipment. It also identifies how the navigation equipment is expected to operate in the NAVAID Infrastructure to meet the operational needs of the Airspace Concept. ICAO navigation specifications provide the basis for the States to develop their certification and operational approval documentation. By the end of 2012, ICAO has published 11 navigation specifications. The present thesis focus on PBN specifications and the proposed solution targets the level of performance associated with some of those specifications.

Navigation Infrastructure refers to ground- and space-based navigation aids.

PBN introduces two kinds of navigation specifications: RNAV and RNP. A fundamental element of RNP specifications is the requirement for On-Board Performance Monitoring and Alerting (OPMA) capability as depicted in Figure 4. This system alerts the pilot if navigation performance requirements suffer any deviation.

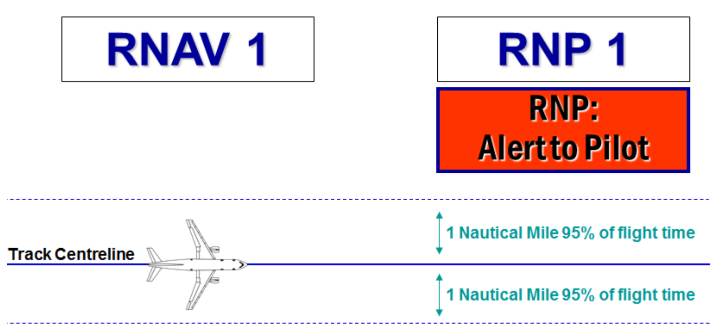


Figure 4 – Difference Between RNAV and RNP
(Source EUROCONTROL)

RNAV specifications are effectively legacy specifications. Indeed, PBN's sights are firmly set on RNP, which relies primarily on the use of satellite technologies. The PBN Manual contains 11 navigation specifications: four of these are RNAV and seven are RNP specifications:

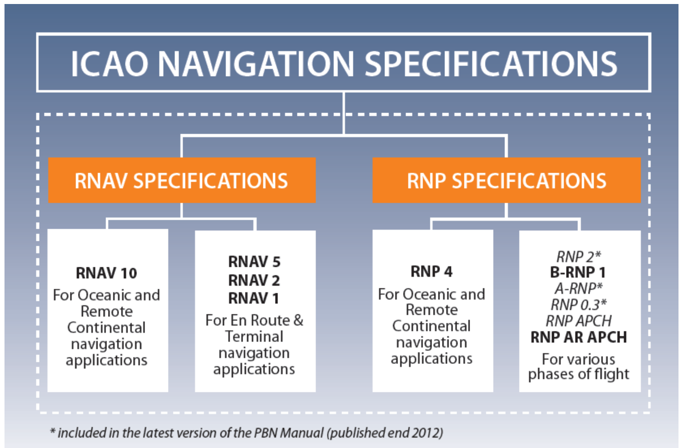


Figure 5 – PBN Specifications
(Source EUROCONTROL)

For subsequent analysis we must retain the most demanding specification, RNP–0.3, closely associated with RNP on Approach. It implies a lateral accuracy of 0.3 NM, or better, meaning the need to ensure that the ranging error is lower than 556.6 meters.

The PBN Manual defines also the so-called "functionalities" (required or optional) which can be used in association with several of the navigation specifications. It is the case, for example, of Radius to Fix, RNAV Holding, Time of Arrival Control and Barometric Vertical Navigation (Baro VNAV).

The final goal is for Advanced RNP specification to become the next European-wide navigation specification used in enroute and terminal airspace, including the approach, missed approach and departure phases of flights. Early drafts of the Advanced RNP specification proposed the flexibility to choose one of a series of accuracy values in each flight phase; this capability is a "Scalable RNP".

It is essential to verify if DME infrastructure can support most PBN specifications, in particular RNP. Multi-DME ranging provides an Area Navigation (RNAV) service with performances up to at least 1NM accuracy (ideally 0.3 NM as previously stated). However, as currently defined, DME/DME positioning may not support RNP navigation specifications that require OPMA alerting. The high level goal of OPMA is to achieve a bound on Total System Error (TSE) at a 10^{-5} per flight hour integrity risk level.

The feasibility of a new system targeted to replace DME to sustain a particular RNP specification, including OPMA[8], is the focus of subsequent discussions on how achievable DME (or the alternative A-PNT system) integrity would be to sustain defined levels of RNP (e.g 0.3 NM = 556.6 m), including OPMA.

Despite impressive progress in navigation capabilities and concepts, there remains much to be done as the rate of aircraft equipage is far from comprehensive and PBN deployment progresses slowly. For the objective of this work it is important to retain that a proposed solution must be compliant with relevant requirements of multitracking area navigation supporting defined PBN specifications. Annex "A" describes one example of a PBN application, taking advantage of particular specifications and functionalities.

2.4 GNSS AND THE NEED FOR A TERRESTRIAL BACKUP

The implementation of PBN will be primarily based on a GNSS space segment operated by entities outside of the remit of aviation and it was designed to fulfill non-aeronautical functions. As stated above, this fact triggered the introduction of GNSS augmentation systems (SBAS, ABAS, GBAS) to achieve the required level of navigation performance needed for aviation operations. The key driver for those augmentation systems is integrity.

However, multiple safety and vulnerability studies [10] [11] have shown that GNSS outages are possible due to solar/ionospheric disturbances, intentional or unintentional interference/jamming, coverage gap due to constellation weakness, or other unexpected GNSS service degradations.

The ionosphere effects are a threat to aviation operations during severe to extreme ionosphere storms. Unintentional interference, in particular interference caused by industrial and commercial in- or out-of-band emissions, is a threat in all urban and industrial areas. Intentional interference, especially spoofing[9], could also be a threat since anti-spoofing techniques are normally a military technology. Jamming can also be a serious threat because intentional jamming is relatively easy to achieve. Future multi-frequency / multi-constellation receivers could be a solution for these threats but residual risks remain.

Based on current experience and considering the potential threats, unexpected outages affecting one or more airspace sectors or one complete Terminal Area (TMA) should be

[8] Considering DME/RAIM instead of GNSS/RAIM

[9] Spoofing, in general, is a fraudulent or malicious practice in which communication is sent from an unknown source disguised as a source known to the receiver. Spoofing is most prevalent in communication mechanisms that lack a high level of security.

"occasional" events. Such qualitative frequency of occurrence could be translated in a quantitative frequency corresponding to an unexpected outage affecting one or more sectors once every 1 to 10 years. However the likelihood for such event might be greater in TMA because interference is more likely at low altitude.

As a consequence, there is broad agreement that some terrestrial navigation infrastructure needs to remain operational in order to mitigate the risk of a potential wide area GNSS outage enabling appropriate reversion scenarios.

2.5 ALTERNATIVE POSITIONING NAVIGATION AND TIMING (A-PNT)

The implementation of PBN is to be primarily based on GNSS. However, despite the introduction of augmentation systems to improve GNSS integrity, the space segment remains vulnerable to service outages due to jamming or solar events.

The abovementioned GNSS outages require the retention of alternative means for the provision of Alternative Positioning, Navigation and Timing. Today´s decisions indicate that the first A-PNT choice is the retention of existing conventional NAVAIDS like DME [12]. Initially, DME will serve as the back up to mitigate unavailability of satellite navigation enablers without prejudice of investigating other A-PNT means that fulfill RNAV and RNP requirements.

Essentially, an alternative navigational functionality suitable for PBN requires an aircraft to be able to perform ranging to several known, typically ground-based ranging sources at known locations. DMEs are one option but other alternatives shall not be discarded. DME stations are often located along air-traffic corridors and, thus, their placement is not optimized for multilateration.

Nevertheless, DME is still seen as the most suitable existing terrestrial navigation aid to sustain PBN. For that, multi-DME ranging shall provide an RNAV service with a minimum performance accuracy of 1 Nautical Mile (NM) (or ideally 0.3 NM). However, as currently defined, DME/DME positioning may not be able to support RNP navigation specifications, which require OPMA (e.g RNP-1 or RNP-0.3). For RNP-0.3 only GNSS enablers are suitable today.

A key advantage of DME is that all system components are under aviation control. DME ground transponders have evolved over many years of service and contain a number of industry standard monitors, which are linked to specific ICAO Annex 10 requirements and recommendations. These monitors detect anomalies and terminate service if required. Some ANSP in Europe have imposed specific integrity monitoring and manufacturers have consequently integrated them into their station designs.

Next, the signal in space propagation issues facing DME are generally well understood due to the long and established service history of DME – there is the potential of multipath, co-channel interference and other effects that can be controlled by a variety of ANSP efforts. This is also true for the historically most prevalent DME error effect, the map-shift due to station coordinate publication errors. Finally, aircraft interrogators and downstream Flight Management System (FMS) processing does include reasonableness checks and in many cases INS integration protects against several avionics-based failure modes, including DME ranging errors.

DME system uses the L-band frequency spectrum very inefficiently (see Figure 6). DME pulses may interfere with Galileo E5a/E5b and GPS L5 signals. Besides, the required DME improvements and complete redesign of the DME infrastructure would severely impact the sustainable use of that spectrum band for communications and navigation [13].

The abovementioned constraints impacting the use of DME as A-PNT call for a different approach. Integrating the navigation functionality into the soon to be deployed next generation of terrestrial data links is one of the potential solutions.

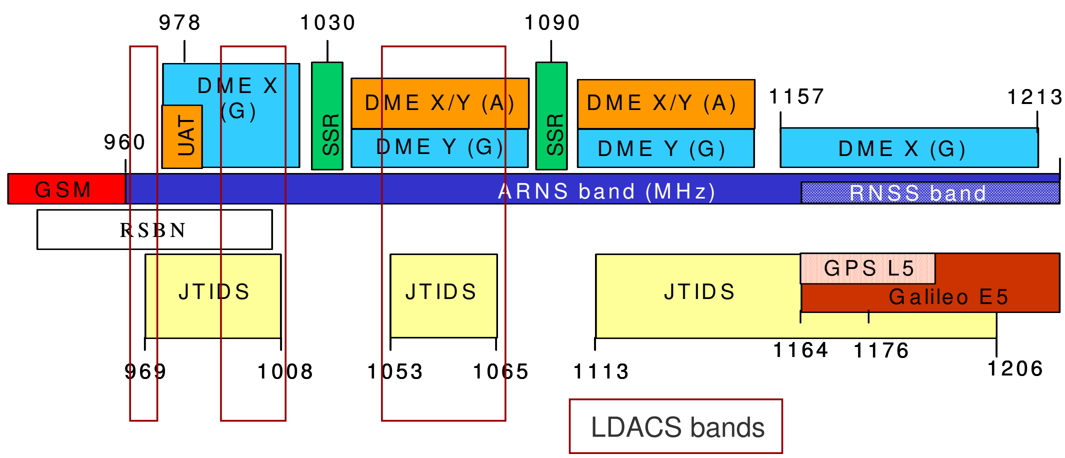


Figure 6 – L-Band Spectrum
(Source EUROCONTROL)

As we will see later, the future LDACS data link ground stations transmit continuously and synchronously in different frequency bands. Each 500 kHz-wide OFDM channel could be utilized as a ranging source. In this way, the navigational functionality could be covered through the implementation of LDACS ground stations.

2.6 DISTANCE MEASURING EQUIPMENT (DME)

In accordance with ICAO Annex 10 Volume 1, DME is a transponder-based radio navigation technology that provides a means of measurement of slant range distance from an aircraft to a selected transponder. This information is available within the limit of coverage prescribed by the operational requirements for the selected transponder. Such measurement considers the propagation delay of transmitted signals. In summary: the purpose of the DME system is to calculate how far an aircraft is from a selected ground transponder.

A complete DME system [14] comprises two main components: an interrogator (aircraft) and a transponder (ground-based). The interrogator and transponder have similar main functional elements: encoder, transmitter, receiver and decoder.

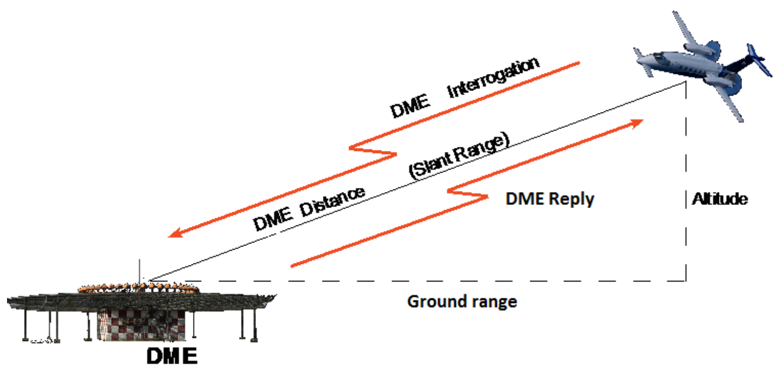


Figure 7 - DME principle
(Source www.edn.com)

The aircraft interrogates the ground transponder with a series of pulse-pairs (interrogations) and, after a precise time delay (typically 50 microseconds), the ground station replies with an identical sequence of pulse-pairs (see Figure 7).

The DME transceiver in the aircraft searches for pulse-pairs (X-mode = 12 microsecond and Y-mode = 36 microsecond spacing) with the correct interval between them, as shown in Figure 8, which is determined by each individual aircraft's particular interrogation pattern. The aircraft interrogator locks on to the DME ground station once it recognizes that a particular reply pulse sequence has the same spacing as the original interrogation sequence. Once the receiver locks, it has a narrower window in which to look for the echoes and can retain lock.

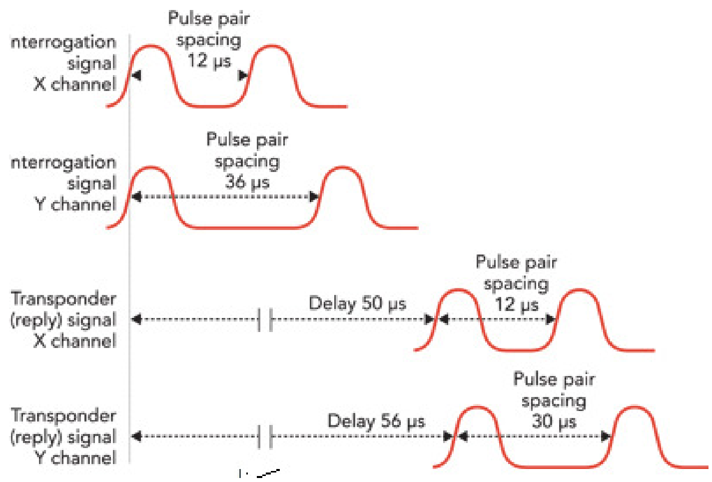


Figure 8 - DME transmissions
(Source www.edn.com)

The interrogator interrogates a single ground transponder, which then transmits a reply following a calibrated fixed delay. The airborne unit then computes the slant range to that ground facility by measuring the elapsed time between the interrogation and the reception of the transponder reply. The measured range is available to the pilot and other aircraft systems as required.

The DME interrogator in search mode transmits up to 150 pulse pairs per second (ppps) on the designated channel. Once valid replies from the transponder are available, the interrogator enters in 'track' mode. In track mode, the interrogator transmits at a lower rate, up to 30 ppps in order to maintain lock in search mode. One should note that these are the maximum permissible transmission rates and most modern interrogators utilise lower rates.

The range from the aircraft to the ground transponder derives from the total round trip time. A clock in the interrogator starts at the 50% point on the rising edge of the first pulse of an interrogation. The clock stops at the 50% point on the rising edge of the first pulse of the received reply. The total round-trip time includes the fixed transponder processing delay, which is 50 μs for an X-channel and 56 μs for a Y-channel. Since the pulses travel at the speed of light, it takes 6.18 μs to cover 1 NM. Therefore, the range to the beacon results from the following equation:

$$Range(nm) = \frac{Total\_Round\_Trip\_Delay - Transponder\_Delay}{12.36} \qquad \text{(Equation 1)}$$

In addition to performing range measurements, the interrogator must also recognise an identification signal transmitted by the transponder. The identification signal consists of on-channel pulse pairs sent at a periodic rate of 1350 ppps, decoded by the interrogator and converted into an audible tone used by the pilot. The identification is a three or four letter Morse Code, uniquely identifying the transponder to which the interrogator is tuned.

For the purpose of the present thesis, it is important to retain the following range-related performance targets (focus on DME/N):

- *Range.* The system shall provide a means of measurement of slant range distance from an aircraft to a selected transponder to the limit of coverage prescribed by the operational requirements for the selected transponder.
- *System accuracy.* The accuracy standards specified in the ICAO Annex 10 shall be met on a 95% probability basis.
- *DME/N.* The transponder shall not contribute more than plus or minus 1 microsecond (150 m (500 ft)) to the overall system error.
- *DME/N.* The interrogator shall not contribute more than plus or minus 315 m (plus or minus 0.17 NM) or 0.25% per cent of indicated range, whichever is greater, to the overall system error.
- *DME/N.* The combination of the transponder errors, transponder location coordinate errors, propagation effects and random pulse interference effects shall not contribute more than plus or minus 185 m (0.1 NM) to the overall system error. This error contribution limit includes errors from all causes except the airborne equipment, and assumes that the airborne equipment measures time delay based on the first constituent pulse of a pulse pair.

Figure 9 – VOR/DME Brussels Airport
(Source BELGOCONTROL)

2.7 DME USE TO SUPPORT AREA NAVIGATION AND TO BACK UP GNSS

As stated before, there is no assurance that DME/DME can be fully recognized as the reversionary capability to GNSS-based PBN operations that require RNP level of performance. This could significantly boost the requirement to deploy new A-PNT systems using new technology. Due to operational requirements foreseen for application in Europe, the present discussion was still limited to RNP-1, e.g., RNP supporting a 1NM (95%) accuracy performance.

DME evidences the following drawbacks for playing that role:

- Path Definition Error (PDE), Flight Technical Error (FTE), Navigation System Error (NSE), described before;
- Malfunction of the transponder which leads to the insertion of a time delay exceeding the specified tolerances (50 μ s ± 1 μ s in X mode or 56 μ s ± 1 μ s in Y mode);
- Multipath effects including downlink multipath propagation which would generate two replies to the same interrogation;
- Reply efficiency drop due to echoes coming from reflectors located in the vicinity;
- Incorrect range information if the transponder replies to both direct path and reflected path interrogations.

<u>DME Errors</u> - The high level objective of OPMA is to achieve a bound on Total System Error at 10^{-5} per flight hour integrity risk level. The TSE is composed of Path Definition Error (PDE), Flight Technical Error (FTE) and Navigation System Error (NSE).

While the PDE is considered negligible, it should be noted that this is enabled by specific avionics functions, namely Fixed Radius Turn (FRT) in the en-route and radius to fix (RF) in the terminal area. These two functions eliminate the path dispersion between route segments, which is typical due to different configurations of aircraft aerodynamics and weight. Without those functions, PDE becomes essentially unbounded over the turns.

FTE depends on the level of aircraft automation – procedure design distinguishes between hand-flown FTE and FTE using an autopilot or flight director. Manually flown FTE has been assumed to achieve accuracies limited to an error of 0.5 NM at a 95% confidence level in RNAV-1 applications. Earlier work has documented Automatic Flight Control System (AFCS)-coupled FTE at a maximum value of 0.22NM when using DME/DME.

Moving on to NSE, the integrity budget for RNP-1 has been specified to require an alert at a 10^{-7} risk level when exceeding twice the RNP value, e.g., 2NM. This is easily met by all current generation GNSS avionics. This will also be sufficient to meet the high level RNP goal of a 10^{-5} TSE bound which includes NSE support to limiting the FTE distribution.

Malfunction of the transponder - The DME slant range is computed by the interrogator based on the propagation delay to and from the transponder, taking into account a fixed delay which is introduced by the latter. As such, in an interrogator fault free scenario, the only integrity threat consists in a corrupted delay of the reply pulses. There are 2 main causes that could affect this delay: Downlink multipath propagation or malfunction of the transponder which leads to the insertion of a time delay exceeding the specified tolerances (50 μs ± 1 μs in X mode or 56 μs ± 1 μs in Y mode). The last problem is addressed through internal transponder monitoring mechanisms to ensure that transponder faults are kept within a certain limit.

Multipath - DME multipath signals, received at the airborne DME interrogator, shall not have an adverse impact on signal quality and the resulting distance accuracy. However, some tests revealed the duration of multipath received at airborne receiver to be about 150 μs in length and only about 25 dB weaker then the direct signal. Multipath effect on DME transponder receiver can cause false replies mainly if aircraft are less than 25 NM separated from a transponder. That is logical since the path loss increases with distance, which in consequence provides a faster drop of the amplitude of the received multipath signals below the noise floor. This effect is mitigated through the application of dead time with variable length after each reply generated by a valid interrogation pulse pair to avoid false replies to that can be caused by delayed signals due to multipath.

While downlink multipath is much more significant it can also be more effectively be mitigated by the ground facility as discussed previously. Due to the motion of the aircraft and the constraints in reflector geometry (e.g., a significant reflection surface is required for sufficient pulse energy to reach the aircraft), uplink multipath is essentially noise-like. While some isolated cases of confirmed uplink multipath have been reported, these remain rare and small in magnitude. In an analysis of multiple DME facilities received over a large number of flight test tracks, it has been demonstrated that the DME 95% range accuracy lies within 0.05 NM. This provides a suitable bound for both nominal noise and uplink multipath performance. However, it should also be noted that this analysis shows distribution deviations up to 0.2 NM which require further investigation.

The measure required by the ICAO Annex 10 to prevent multipath effects is the introduction of a “DME dead time: a period immediately following the decoding of a valid interrogation during which a received interrogation will not cause a reply to be generated”. The dead time is normally set to 60 µs. The 60 µs interval already prevents the decoding of echoes with a propagation path difference up to 10 NM. It is obvious that reflected interrogation with a delay higher than 60 s can only be produced by extremely large reflectors (i.e. natural terrain features like mountain sides).

The probability of echoes with a higher propagation delay appears to be very low; however, transponders generally comply with the recommended capability to reject long distance echoes arriving with a delay up to at least 120 s. The increase of the dead time may impact on the other hand the reply efficiency. For this reason several rejection techniques may be used (e.g. only signals with the power level several dB below the valid interrogation are rejected in the extended dead time, or a variable duration dead time window is used).

The risk of receiving another DME beacon reply far away that has been allocated to the same channel appears to be one of the most relevant threats to DME-based positioning integrity, with the potential to lead to significant range measurement errors, particularly if the desired station is out of service.

Additional noise from TACAN is not considered to be relevant from a range error perspective and is normally filtered out especially when considering the normal resolution of avionics DME range outputs (resolution is typically not greater than 0.01NM or 18m), but may have an impact on the ability of avionics to detect errors.

<u>Reply efficiency drop</u> - This effect may appear due to echoes coming from reflectors located relatively close to the ground stations so that the additional time delay is less than the interrogation pulse spacing (12 µs ± 0.25 µs in X mode respectively 36 µs ± 0.25 µs in Y mode). In this case the decoder would detect a spacing value that is out of tolerance and would reject the interrogation. Recent flight test evidence supports that this short distance echo suppression mechanism is working well. Although this may cause a continuity issue, it is not considered a threat to integrity.

Incorrect range information - This type of issue may appear if the transponder replies both to direct path and reflected path interrogations. In this case, in certain circumstances the interrogator may lock onto the second set of replies in which case the calculated range will be higher than the real one. The mitigation measures implemented in the transponder in order to cater for this potential integrity issue are described below.

The acceptable DME/N overall system error (which determines the acceptable range performance) results from the interrogators and transponder cumulative contributions identified above: 185 m (0.1 NM) + 315 m (0.17 NM) = 400m (0.27 NM). ICAO Annex 10 describes the full set of DME technical parameters and filters used to maximize performance.

It is important to stress again that Inertial Navigation System integration can protect against several avionics-based failure modes, including DME ranging errors.

There is a risk is that the aviation community may reject DME/DME as a reversionary backup capability to GNSS-based PBN operations which require RNP performance. This could significantly diminish the future value of the significant levels of fielded equipage, both on aircraft and on the ground. It will also firm up the requirement to deploy new A-PNT systems using new technology.

3 AIR-GROUND DATA LINK TECHNOLOGIES

3.1 CURRENT TECHNOLOGIES

Air ground VHF voice communications[10] remains a key enabler for the exchange of information and instructions between the aircraft and ground ATC. Voice is still the primary means for pilots to communicate with air traffic controllers.

This form of analogue communications is now reaching its operational limits and the aviation community started to implement air-ground digital data communications (thereafter designated “data links”) to support and, at a later stage, replace voice as the primary means of ATC communication. Voice remains available only for emergencies.

Figure 10 – Example of CPDLC page on MCDU. Voice frequency change confirmed by the pilot
(Source EUROCONTROL)

The need for air-ground data links is justified by performance objectives but also by the need to increase safety. Studies have demonstrated that up to one in three voice communications is

[10] Air-ground voice communications use analogue double side band AM with 25 kHz or 8.33 kHz channel spacing relying on the allocated VHF spectrum band between 118-137 MHz.

misunderstood and that controllers spend up to 50% of their time talking to pilots.

Data links connect pilots to controllers to support routine communications (exchange of pre-defined short messages). In the context of ATC this is called Controller-Pilot Data Link Communications (CPDLC). CPDLC[11] sustains applications[12] like the initiation of the communications service, ATC clearances (departure, climb or descent), management of repetitive frequency changes and microphone check. This service is already operational in some of the European core-area states. Subsequently, additional applications to support trajectory management will need the Automatic Dependant Surveillance – Contract (ADS-C) technique relying also on the use of VDL Mode 2 [15].

Later, there are plans to implement ATC applications supporting the uplink of Aeronautical Information Services (AIS) and Meteorology. Other applications will become operational for Airport Services, Airline Operational Communications (AOC) and Airline Passenger Communications (APC).

CPDLC relies on communications architectures, services and protocols compliant with the ICAO Aeronautical Telecommunications Network (ATN) initially using Open System Interconnection (OSI) protocol stack. Subsequently, ATN will use the Internet Protocol Suite (IPS) as described in ICAO document 9896 [16].

Data link equipment like the Aircraft Communications and Reporting System (ACARS) or the VHF Data Link Mode 2 are technologies in the VHF band used today to support CPDLC. The latter is the choice for deployment in Europe and it was subject of SES regulatory measures with ground implementation and aircraft equipage mandated by the European Commission Regulation 29/2009 of 16 January 2009 on Data Link Services. The companies ARINC and SITA are the main CPDLC service providers worldwide.

VDL2 radio technology relies on spectrum in the upper part of the band 118-138 MHz. The VDL Mode 2 Link Layer comprises two sublayers, a data link service and a Medium Access Control (MAC) sublayer. The data link protocol relies on the ISO standards used for dial-up HDLC access to X.25 networks. It provides aircraft with a positive link establishment to a ground station and defines an addressing scheme for ground stations. The MAC protocol is a version of Carrier Sense Multiple Access (CSMA). The VDL Mode 2 Physical Layer specifies

[11] It is of utmost importance not to mix the ATC applications and messages (normally standardised at EUROCAE/RTCA level), further described later in this chapter, with the data link technology infrastructure that supports information exchange**.**

[12] Applications in this context means message formats and protocols standardised by EUROCAE

the use in a 25 kHz wide VHF channel of a modulation scheme called Differential 8-Phase-Shift-Keying with a symbol rate of 10.500 symbols per second. The raw (uncoded) physical layer bit rate is 31.5 kbit/s; clearly insufficient to support future requirements.

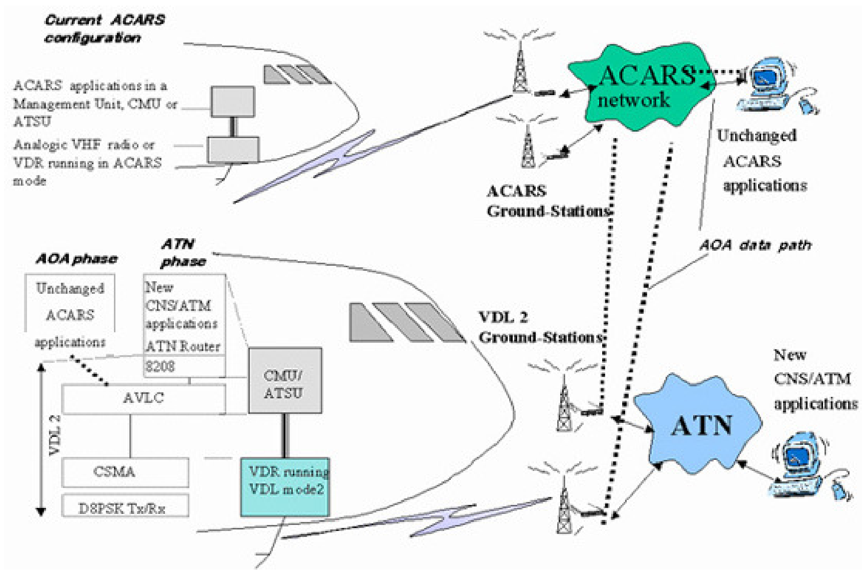


Figure 11 – CPDLC Context
(Source EUROCONTROL)

3.2 FUTURE COMMUNICATIONS INFRASTRUCTURE (FCI)

As we saw before, the ATN/VDL Mode 2 technology is rather limited and will need enhancements or complements to support the new features of the Air Traffic Management concepts beyond 2020. Higher performance (bandwidth and integrity) data links will be required to support advanced services. To respond to those challenges ICAO decided to plan new technologies, globally designated Future Communications Infrastructure (FCI or Future COM).

Under their Memorandum of Cooperation, the U.S. Federal Aviation Administration (FAA) and EUROCONTROL have been working to identify such new FCI system(s), planned for deployment from around 2020 defining technical parameters such as capacity, throughput, access time, quality of service and security. The airborne solution is referred to as the Future Radio System (FRS).

FCI comprises three segments: a ground-based high-capacity airport surface data link system, referred to as the Aeronautical Mobile Airport Communications System (AeroMACS), a satellite-based data link system (SATCOM) for the oceanic, remote and continental environments and a ground-based terrestrial data link system for continental airspace in general, referred to as the L-Band Digital Aeronautical Communications System (LDACS).

Taking into account the identified requirements, several candidate technologies for the FRS (Satellite Communications, Terrestrial Wideband CDMA, Cellular Telephony, UMTS, TDMA, Software Defined Radios, Broadband VHF, etc.) were assessed and the most promising ones would be analysed in detail and prototyped.

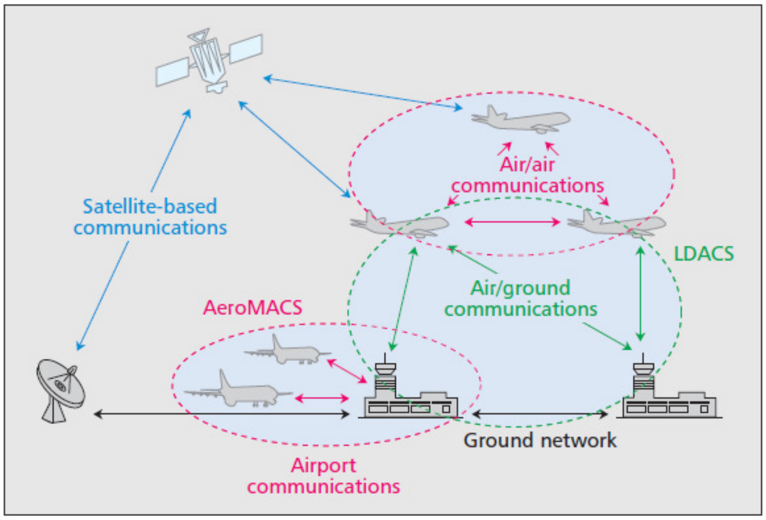


Figure 12 – Future Communications Infrastructure (FCI)
(Source EUROCONTROL)

The terrestrial component of FCI, LDACS, relies on spectrum allocations (960-1215 MHz) agreed at the level of the International Telecommunications Union (ITU) and it is still being subject of industrial research, in the context of the SESAR work programme, to determine the final technology solution to be chosen between Frequency Division Duplex (FDD) utilizing OFDM modulation and Time Division Duplex (TDD) combined with Gaussian Minimum Shift Keying (GMSK)[13] modulation.

3.3 L-BAND DIGITAL ATM COMMUNICATIONS SYSTEM (LDACS)

ICAO selected two candidate terrestrial technologies for the future digital air-ground communications system. These technologies have been designated: LDACS1 and LDACS2. LDACS2 is based on Global System for Mobile Communications (GSM). It is a narrowband single-carrier system with 200 kHz transmission bandwidth and time-division duplex.

The present thesis focuses on LDACS1, as it is clearly the option retained for further

[13] GMSK is a continuous-phase frequency-shift keying modulation scheme. It is similar to standard minimum-shift keying (MSK); however the digital data stream is first shaped with a Gaussian filter before being applied to a frequencymodulator.

development. LDACS1 is based on OFDM waveform, which is a state-of-the-art broadband waveform, resistant to multipath propagation and scalable to high-capacities, similar to the waveforms currently used in broadband systems like wireless Local Area Networks (LAN) (Wi-Fi), Long-Term Evolution (LTE) [17] and WiMAX (IEEE 802.16) [18], as well as in digital broadcast systems (DAB, DVB-T, DVB-S). LDACS benefits from the European B-VHF project, U.S. TIA-902 (P34) and WiMAX technologies. OFDM uses orthogonally overlapped sub-carriers, each of which conveys part of the data (hence, each sub-carrier operates under narrow-band condition and is naturally immune to multipath effects). The forward and reverse channels operate under a FDD scheme.

In order to avoid sharing this limited bandwidth between forward and reverse links, frequency-division duplex is applied. Note that the link from the ground station to the aircraft is referred to as forward link, and the link back from the aircraft to the Ground Station (GS) is called reverse link. LDACS1 offers two modes of operation, one for air-ground (A/G) communications and another one for air-air (A/A) communications. These two modes use different radio channels.

LDACS1 operating in the A/G mode is a cellular point-to-multipoint system. The A/G mode assumes a star-topology where Airborne Stations (AS) belonging to aircraft within a certain volume of space (the LDACS1 cell) are connected to the controlling GS. The LDACS1 GS is a centralized instance that controls the LDACS1 A/G communications. The LDACS1 GS can simultaneously support multiple bi-directional links to the ASs under its control.

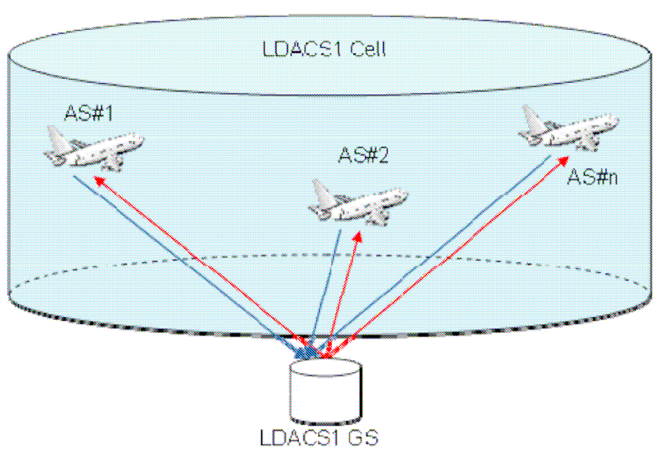


Figure 13 – LDACS1 Topology
(Source www.lit.lnt.de)

In order to maximize the capacity per channel and to optimally use the available spectrum, LDACS1 is defined as an OFDM-based FDD system, supporting simultaneous transmission in

Forward Link (FL) and Reverse Link (RL) channels, each with an occupied bandwidth of 498.05 kHz. Within that bandwidth 50 OFDM sub-carriers are placed separated by 9.765625 kHz. Each sub-carrier is separately modulated, the total duration of each modulated OFDM symbol is Ts= 120 µs. The OFDM parameters have been selected taking into account specifics of an aeronautical mobile L-band channel.

LDACS1 A/G design includes propagation guard times sufficient for the operation at a maximum distance of 200 NM from the GS. At this distance, one-way propagation delay is 1.26 ms, roughly corresponding to the duration of 10 LDACS1 OFDM symbols. Large target operational coverage imposed some constraints upon the LDACS1 PHY layer design (definition of PHY frames). In a practical deployment, LDACS1 can be designed for any range up to this maximum range.

The LDACS1 framing structure (Figure 14) for FL and RL is based on Super-Frames (SF) of 240 ms duration. Each SF corresponds to 2000 OFDM symbols. The FL and RL SF boundaries are aligned (from the view of the GS).

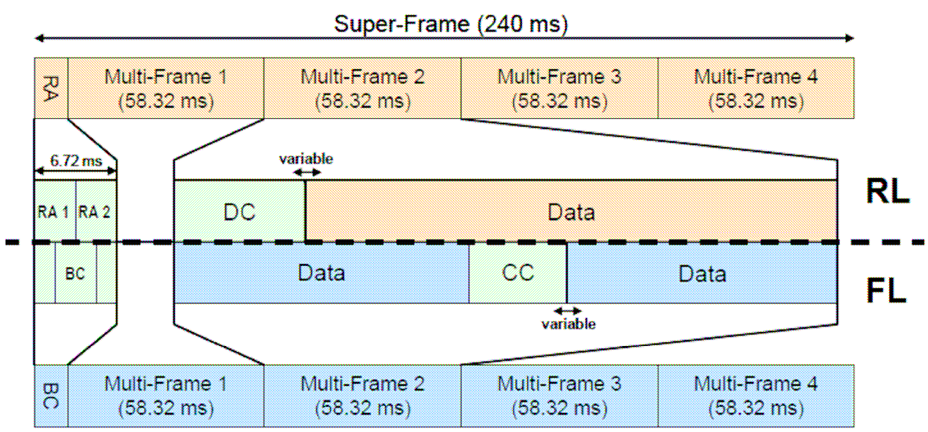


Figure 14 - LDACS1 Framing Structure
(Source [22])

In the FL, an SF contains a Broadcast Frame (BC) of duration TBC = 6.72 ms (56 OFDM symbols), and four Multi-Frames (MF), each of duration TMF = 58.32 ms (486 OFDM symbols). Each MF contains 9 Data/CC frames with a frame duration of TDF/CC = 6.48 ms (54 OFDM symbols). Each Data/CC frame has a total data capacity of 2442 symbols and comprises exactly three FL PHY-PDUs that are used for transmitting either the common control (CC) information or payload data.

In the RL, each SF starts with a time slot of length TRA = 6.72 ms with two opportunities for sending Reverse Link Random Access (RL RA) frames, followed by four MFs. These MFs have the same fixed duration of TMF = 58.32 ms as in the FL, but a different internal structure. Within the RL MF, instead of frames, data and control (DC) segments are used that are further divided into tiles. A tile spans a specified number of contiguous symbols, both in frequency and time direction. The size of an RL Data PHY-PDU and an RL DC PHY-PDU corresponds to the number of modulated data symbols of a corresponding DC/Data tile.

LDACS1 is intended to operate as a FDD system in the lower part of the L-band (960-1164 MHz). An airborne LDACS1 system (AS) using FDD with a single airborne antenna relies upon an airborne TX/RX duplexer. Due to the duplexer feasibility, the blocks of FL and RL channels must be sufficiently separated in frequency domain. 40 MHz has been assumed to be the minimum practical width of a transition area for an airborne duplexer. This value should be confirmed. Larger transition areas above 40 MHz (and larger duplex spacing above 63 MHz) are considered feasible as well. Several options are still under discussion for the deployment of LDACS1 in the lower part of L-Band [19] [20].

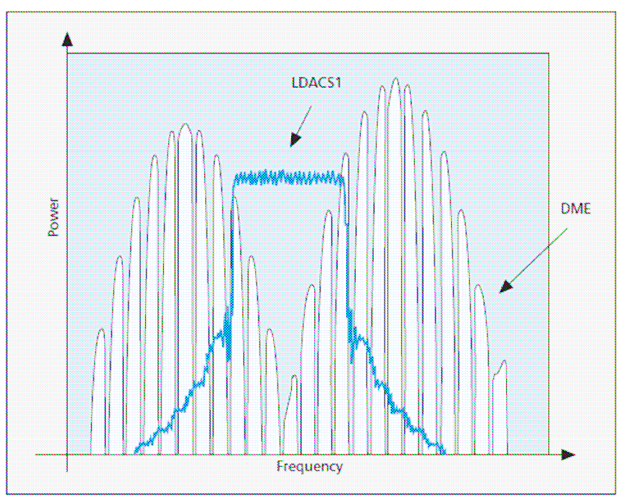


Figure 15 – Insertion of LDACS1 in the L-Band
(Source IEEE Journal)

When operating in A/A mode, the LDACS1 system offers a broadcast A/A surveillance link and an addressed (point-to-point) A/A data link, both with direct air-air connectivity. A/A communication, between involved LDACS1 AS, takes place in a decentralized, self-organised way without any need for ground support (GSs may be optionally deployed, e.g. for monitoring A/A traffic). For A/A network synchronization purposes, the availability of a common global time reference is assumed at each AS. No A/A voice services are offered in this mode.

LDACS1 operating in A/A mode assumes a dedicated global RF resource, the "Common Communications Channel" (CCC). The LDACS1 A/A mode uses an OFDM-based physical layer with parameters (e.g. subcarrier spacing) different than those used for the A/G mode. As it will be seen later, this feature of LDACS1 will be essential for an innovative proposal for a navigation function to be supported.

LDACS1 is expected to provide coverage of up to 200 NM, corresponding to a cell radius of approximately 370 km. This leads to large propagation delays of up to 1.2 ms. Particularly in the case of an unsynchronized transmission sufficiently large guard times have to be foreseen in the system design. In addition, such a large coverage area results in a high number of users (i.e., aircraft active within a cell).

LDACS1 has to support very high user mobility leading to large Doppler shifts. The expected maximum aircraft velocity of 1080 km/h leads to a Doppler shift of approximately 1 kHz assuming a radio carrier frequency of 1 GHz. If aircraft fly in opposite directions, their messages may arrive with a frequency offset of 2 kHz at a ground station. To relieve this issue, appropriate guard bands or frequency pre-compensation have to be foreseen. Although the Doppler shifts might be very high, only slight Doppler spreads are expected due to a strong line of sight path.

To set up the cellular LDACS1 concept, adjacent cells use different paired transmission channels for forward and reverse links. Cells farther apart might reuse already assigned channels if interference towards other LDACS1 cells is negligible. To establish communication, an aircraft has to register at the ground station of the respective LDACS1 cell. For this cell entry, LDACS1 provides periodically occurring random access opportunities in the reverse link. Due to the potentially large propagation delays, they are protected by appropriate guard times.

After cell entry, the controlling ground station assigns a dedicated control channel to the aircraft. This dedicated control channel guarantees timely channel access for the aircraft, which is important for the latency requirements of ATM services. In addition, the ground station measures the propagation delay and frequency offset of the random access messages during cell entry. These values are conveyed to the aircraft to enable pre-compensation of the time and frequency offset at the aircraft.

In this way, messages of all aircraft arrive synchronously at the ground station despite the possibly large propagation delays and frequency offsets. No further guard times and bands are required. Besides cell entry by means of random access opportunities, LDACS1 provides a seamless handover procedure for already registered aircraft passing from the current to an adjacent cell. This is possible because the ground stations are synchronized with each other. The seamless handover enables continuous communications between ground station and aircraft, and relieves usage of random access opportunities.

LDACS1 achieves net data rates from 561 kbit/s (strong coding, robust modulation) to 2.6 Mbit/s (weak coding, higher order modulation) for a pair of forward and reverse link channels (Table 1).

To account for a varying number of active aircraft and the current demand for user data transmission, the size of the control and data segments is variable. Furthermore, resources for the different users are dynamically assigned according to the current demand. To provide the required granularity for the mostly short ATM messages, the reverse link framing is subdivided into small tiles as explained before. An arbitrary number of these small tiles can be aggregated and assigned to an aircraft depending on the actual message size. This is no issue in the forward link, since multiple messages intended for different aircraft are grouped and broadcasted to all aircraft. Each aircraft receives the entire frame and extracts its message.

LDACS1 system parameter	Value
OFDM size	64
Number of used subcarriers	50
Total OFDM bandwidth	625 kHz
Effective bandwidth	498 kHz
Subcarrier spacing	9.77 kHz
OFDM symbol duration	102.4 μs
OFDM guard interval duration	4.8 μs
Transmit window duration	12.8 μs
Total OFDM symbol duration	102.4 ms + 4.8 ms + 12.8 ms = 120 μs
Sampling interval	1.6 ms
Minimum net data rate (QPSK, strong coding); combined forward and reverse link	561 kb/s
Maximum net data rate (64-QAM, weak coding); combined forward and reverse link	2.6 Mb/s

Table 1 – Summary of Main LDACS1 Parameters
(Source [22])

Strong channel coding is applied by concatenating Reed-Solomon and convolutional coding schemes. To account for changing interference and channel conditions as well as different message priorities, LDACS1 supports adaptive coding and modulation. In the case of strong interference or high-priority messages, a low coding rate and robust modulation scheme is chosen, such as Quadrature Phase Shift Keying (QPSK). For favorable transmission conditions, a high coding rate and/or higher order modulation, such as 16- or 64-Quadrature Amplitude Modulation (QAM), can be used to increase the transmission capacity.

It is very important for the subsequent analysis to mention that the initial LDACS1 specification [21] [22] indicated the need to reach a Bit Error Rate (BER) of 10^{-6} or less after Forward Error Correction (FEC). Although that BER is not directly associated with ranging performance, it is assumed in the present thesis that it will solve the multipath/Doppler shift problems enabling accuracies far better than the 556.6 meters required for RNP-0.3 (see further details in section 5).

3.4 OTHER DATA LINK TECHNOLOGIES

To support surveillance applications where transmission delay (latency) is more stringent, there is also a requirement for the introduction of broadcast data links to sustain the Automatic Dependent Surveillance–Broadcast (ADS-B) technique. The selected broadcast datalink for ADS-B in Europe is the Mode S 1090 MHz Extended Squitter and in U.S. a combination of Mode S 1090 MHz Extended Squitter (global system for ADS-B) and Universal Asynchronous Transceiver (UAT).

In other regions of the world point-to-point data link technologies are used, as it is the case of services based on ARINC 622 (FANS1/A) specifications [23]. In some northern European regions, the VHF Data Link Mode 4 (VDL-4) is used.

Out of such additional technologies, only Mode S is under investigation to determine its suitability to be reutilised as a means of A-PNT. This new technology designates as Mode N. It is not considered in the present thesis as it would rely on 1030/1090 MHz, which are frequency channels close to reach saturation.

4 RELATIVE NAVIGATION (RELNAV)

4.1 RELNAV CONCEPT

The objective of Relative Navigation is to determine the distance between two or more communication terminals by measuring the arrival times of the transmissions and correlating with reported positions. That problem involves the need for automatic, reliable and accurate relative positioning of two moving vehicles or one vehicle when referenced to ground based radio sites.

A Kalman filter [24] (see annex B) can be used for estimating the relative position and attitude[14] of two air vehicles, designated leader and follower. All leader states are assumed known, while the relative states are estimated using line-of-sight measurements between the vehicles along with acceleration and angular rate measurements of the follower.

4.2 RELNAV ENABLED BY MILITARY DATA LINKS (MIDS/LINK 16)

The military data link JTIDS/MIDS[15] Link 16 is a type of military tactical data exchange network widely used by many military organisations. With Link 16, military aircraft as well as ships and ground forces may exchange tactical picture in near-real time. Link 16 supports the exchange of text messages, imagery data and provides two channels of digital voice. Link 16 is defined as one of the digital services of the NATO's Multifunctional Information Distribution System (MIDS) which technical characteristics are described in the *Standardization Agreement* STANAG 4175 and message set in STANAG 5516.

Link 16 uses the Time Division Multiple Access (TDMA) technique that divides time into discrete time slots to provide multiple and apparently simultaneous communication channels. The MIDS data terminal is the communications component of Link 16. This type of network is very difficult to organize and manage due to the static assignment of time slots and, as a result, there are different Link 16 network settings for specific missions or areas of operation.

A group of radio terminals, using a frequency hopping technique that allows data transmission over the available 51 different career frequencies, composes the Link 16 network. This TDMA

[14] Not to confuse with “altitude”. In the aeronautical context “attitude” means: orientation of an aircraft's axes relative to a reference line or plane, such as the horizon. Given by the attitude indicator (AI)
[15] Joint Tactical Information Distribution System / Multifunctional Information Distribution System

technique allows multiple simultaneous networks to remain in operation through the redundant use of the “Time Slots”, transmitting data inside each network with different frequency. The frequency does not remain constant during a time slot, but it varies every 13 µs according to a pseudo-random pattern of preset jump (frequency hopping) between the 51 available frequencies [25].

The different networks are set according to this jumping pattern. There are 128 networks available. During any time slot, one unit can be transmitting or receiving from any of the available networks. Link 16 contains a variable number of words (usually, 1, 2 or 3), although messages of a length up to 40 words are possible. Each word contains 70 bits. In one “time slot” of 7.8125 ms 3, 6 or 12 words can be transmitted, depending on the type of packing structure used (Standard, Packed-2 or Packed-4).

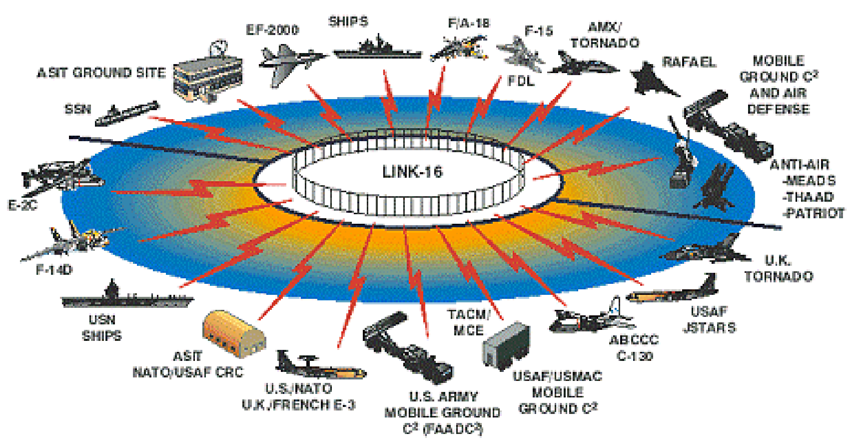


Figure 16a – Military Data Link JTIDS/MIDS Link 16 – Network Participation
(Source What is Link 16?)

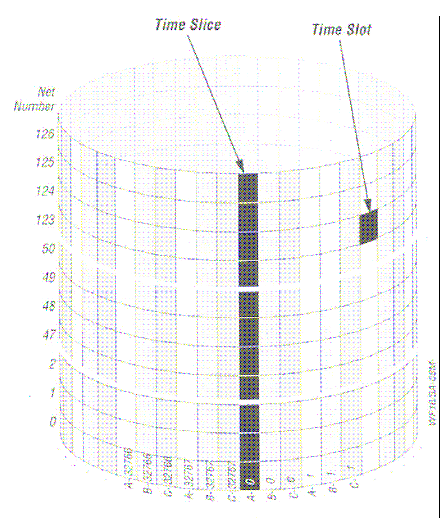


Figure 16b – Military Data Link JTIDS/MIDS Link 16 – Stacked nets

(Source SESAR 15.2.8)

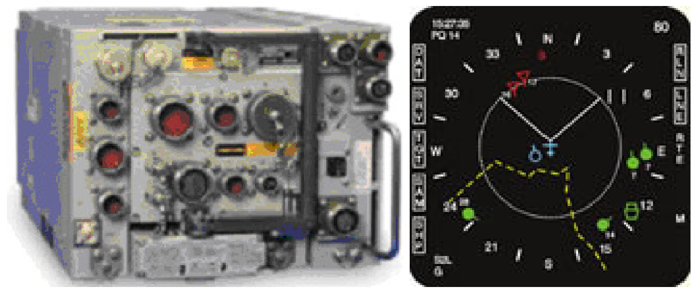


Figure 17 – Military Data Link JTIDS/MIDS Link 16 – Equipment and HMI
(Source What is Link 16?)

In the military context, relative navigation [26] is an automatic function of the military data link (JTIDS/MIDS Link 16) terminal, used to determine the distance between platforms by measuring the arrival times of transmissions and correlating them with reported positions. This information is required for the terminals in a network to remain synchronized.

Automatic RELNAV is permanently available in all airborne terminals, providing information critical for synchronization. This RELNAV data improves unit's positional accuracy. If two or more units have accurate and independent knowledge of their geodetic positions, RELNAV can provide all units of the network with accurate geodetic positions. As a result, the precise geodetic position of every unit can be permanently available at every other unit.

RELNAV function is inherent to the TDMA architecture and the synchronization process. Each airborne terminal continuously calculates its own position by measuring the Times of Arrival (TOA) of all received Precise Participant Location Information (PPLI) messages. As such, RELNAV allows the terminal to calculate an accurate value for the range between itself and another Link 16 transmitting unit. This very accurate range measurement is possible because of the precise timing the terminal must maintain after achieving synchronisation with the network.

The following figure (18) illustrates how the terminal calculates its own relative position. First, consider a terminal that receives a PPLI from another unit. The upper left part of the figure represents a PPLI received from a single source. From the PPLI´s TOA, the receiver can calculate that its position is somewhere on the circle whose radius is the calculated range. In the upper right of the figure, the position source has also provided a value for Position Quality (Q_p) in its PPLI. From the TOA and the Q_p the receiver can calculate that its own position is somewhere within the outer ring shaded area of the circle, and its range is somewhere between the inner and outer edges of the shaded ring whose width defines its position uncertainty.

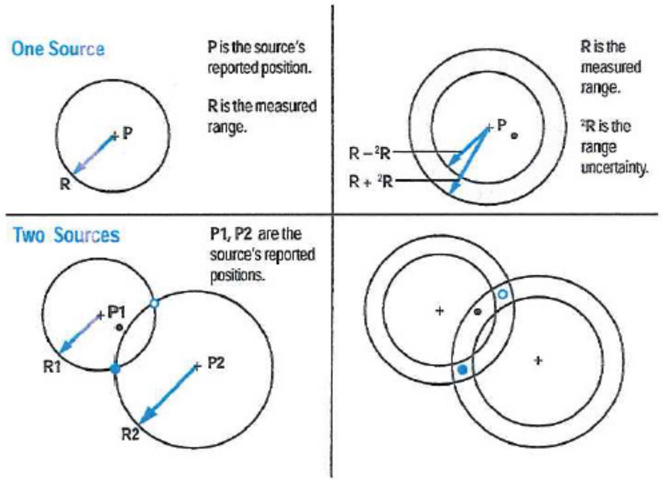


Figure 18 – Link 16 Range Calculation Process

The figure shows the process by which a Link 16 terminal calculates its range and range uncertainty from one or more units. The greater the number of units from which a terminal receives PPLIs, and the higher their reported position qualities are, the more accurately the terminal can calculate its range from them, as well as its own position relative to them.

Now consider a terminal that receives PPLIs from two units. As shown in the lower left part of the figure, the terminal can calculate that it is located at one of two positions where the two range circles intersect. With a rough knowledge of position, the terminal can then decide which one is correct.

Receiving PPLIs from additional units further contributes to the terminal´s position accuracy. The lower right part of the figure shows the calculation with Q_p from the two units. The shaded ring intersection with the solid dot represents the terminal´s own position, as well as a measure of its own Q_p. The value for Q_p can range from 0 (indicating that its position uncertainty is greater than 18.080 feet) to 15 (indicating that its position uncertainty is within 50 feet). The terminal will then transmit this calculated value for Q_p in its own PPLI – until it calculates a different value based on different TOAs and Q_p values from the other network units from which it receives messages.

The terminal can use its relative navigation capability to perform two types of navigation. In fact, the military RELNAV process uses a Kalman filter to estimate position and velocity solutions in two separate grids, the Relative Grid (REL GRID): u,v,w and the Geodetic Grid (GEO GRID): latitude, longitude, altitude.

Relative Grid Navigation – The terminal may be initialised for relative grid navigation whenever the network contains no PR (Position Reference) and participants do not have a highly accurate knowledge of their own position, such as from a GPS source. The parameters affecting this choice, as well as more detailed descriptions of navigational types, are outside the scope of this description.

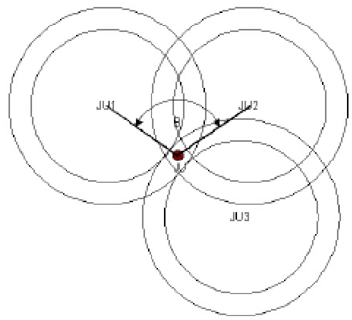


Figure 19 – RELNAV with multiple participating units

The RELATIVE GRID structure is a flat plane grid with 1024 nautical square miles. The plane is tangent to the earth at the Grid Origin. Units estimate their position in the U (east), V (north), and W (altitude) coordinate system and report in feet from the Grid Origin estimate. Proper operation of the grid requires that a unit has the role of Navigation Controller (NC) (and optionally a Secondary Navigation Controller) and that all participating units initialize a common Grid Origin. The REL GRID is not required for proper link operation and is optional.

Geodetic Navigation – or the exchange of position through actual latitude and longitude coordinates in PPLIs. This type of navigation provides position with respect to the ground. For geodetic navigation to be accurate, however, some network participants must have a very good knowledge of their own position – for example, a well-surveyed land site (such as a PR), or a platform equipped with a GPS. The terminal always performs geodetic navigation.

The GEODETIC GRID uses the standard Latitude/Longitude/Altitude coordinate system. Each unit automatically computes its position (and quality) and broadcasts it in its PPLI. The solution is computed by using own unit provided navigation data coupled with received PPLI data. This allows units with high quality fix information (i.e., GPS) to improve the latitude and longitude estimates of every other participant.

In summary, each terminal uses navigation information and PPLI navigation information provided by the host to calculate its position and to estimate the accuracy of that position within these two grids. Broadcast of these elements goes in the PPLI to all other participants.

Figure 20 shows the process by which a Link 16 terminal calculates its range and range uncertainty from one or more other units. The greater the number of units from which a terminal receives PPLIs and the higher their reported position qualities are the more accurately the terminal can calculate its range from them, as well as its own position relative to them. The process shown above is geodetic navigation.

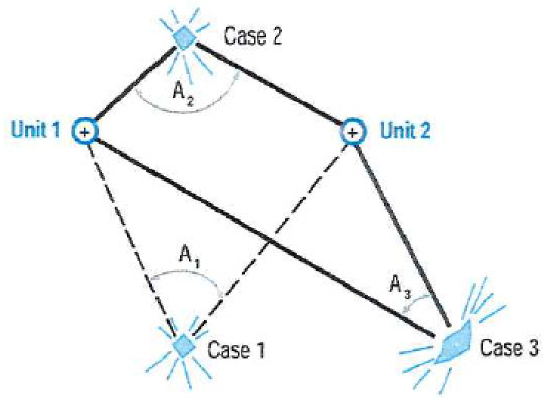


Figure 20 – Geodetic Navigation.

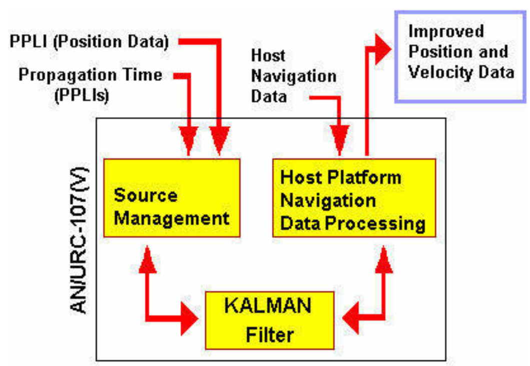


Figure 21 – JTIDS/MIDS RELNAV

Position and velocity data transmitted to the host platform enable display, fixing, or in-flight alignment purposes. The use of this information and the selection of the grid-type shall be consistent with the host platform implementation.

RELNAV accuracy benefits from the availability of high quality users, good relative motion between sources, good geometry and time in the network.

The JTIDS terminal can initiate the navigation resets, automatically or manually, by an operator. Automatic resets may occur when the terminal is changing navigation modes, when information is inconsistent, etc. They are transparent to the operator in active sync (a momentary drop of position quality may be seen), but may cause a loss of fine sync when operating passively. Reoccurring automatic resets can indicate that another user is broadcasting overly optimistic qualities in its PPLI or that problems with own unit navigation processing exist. Manual resets are needed to correct unusually poor PPLI track correlation or navigation errors.

As PPLI is permanently exchanged between all platforms, it is important to highlight that air-air interactions are permanent in RELNAV and transmission delays are always available. The use of the same principles in the ATM context could drastically increase the potential benefits that RELNAV can offer well beyond the limited use of air-ground segments for ranging.

5 FEASIBILITY ASSESSMENT AND SIMULATIONS

5.1 LDACS1 EXTENSION TO NAVIGATION

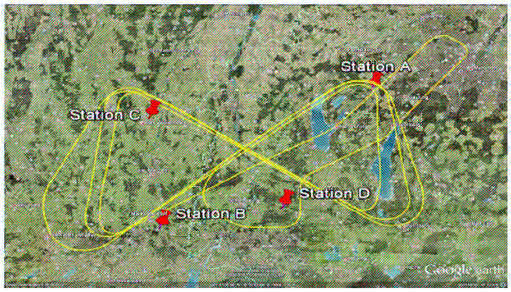
In previous chapters the technical characteristics of the DME NAVAID, targeted for replacement, and those of the potential A-PNT enabler, LDACS1, have been described. As a potential contribution for synergies, we have also described how military data link technology supports relative navigation. With all these elements, we are now in position to assess if LDACS1 can offer the required ranging performance for a certain level of PBN navigation specifications.

Each 500 kHz-wide LDACS1 OFDM channel can be utilized as a ranging source as ground stations transmit continuously and synchronously in different frequency bands. The intended navigation performance shall take advantage of the planned implementation of LDACS1 ground receiver sites (acting as "pseudolites").

LDACS1 feasibility for A-PNT service was already subject of some initial flight trials, conducted in November 2012 by the German Aerospace Center (Deutsches Zentrum fur Luft- und Raumfahrt - DLR) under the auspices of a project designated LDACS-NAV [27]. The ranging results obtained considered four stations to estimate the aircraft position in 3D and a clock offset at the single receiver installed onboard a research aircraft (Dassault Falcon 20E).

The hardware components of each ground station included a Rubidium (Rb) atomic clock reference, a GPS time receiver for off-line station synchronization, an arbitrary waveform signal generator to generate bandpass versions of an LDACS1 signal and a power amplifier with appropriate bandpass filters to reduce out-of band emissions. The GPS receiver was included in the installation set up also to validate the measured range and positioning information. The range estimates obtained with LDACS1 signals were subject of verification against GPS-derived data.

The flight trials used the four ground stations mentioned above transmitting an LDACS1 signal with 10 W transmitting power. The operated channels used the lower part of L-band, between 965-975 MHz.



Distance [km] from/ to	A	B	C	D
A - f = 973.75 MHz 48° 5'8.91"N, 11° 16'37.46"E	-	60	50	36
B - f = 971.25 MHz 47° 45'5.53"N, 10° 38'48.20"E	60	-	30	30
C - f = 968.75 MHz 48° 0'58.99"N, 10° 36'48.63"E	50	30	-	39
D - f = 966.25 MHz 47° 50'4.57"N, 11° 6'59.38"E	36	30	39	-

Figure 22 – Ground stations, location, frequencies and flight distances
(Source [27])

The LDACS1 transmission signal used in the experiments was in accordance with the LDACS1 forward link specifications. Each transmission included four OFDM superframes followed by a 40 ms pause. This originated 8000 OFDM symbols per second considered for ranging. There was a random generation of the OFDM symbols so that the peak to average power ratio can be limited.

Parameter	Value
Bandwidth	500 kHz
Nominal transmit power	39 dBm
DFT size	64
Used subcarriers	50
Subcarrier spacing	≈ 9.7 kHz
Superframe (SF) length	240 ms
OFDM symbols in SF	2000
Sampling time	1.6 µs
Total symbol duration	120 µs
Windowing duration	12.8 µs
Cyclic prefix duration	4.8 µs

Figure 23 – LDACS1 transmission parameters
(Source [27])

The 90 minute flight conducted at flight levels FL100 (≈ 3000m), FL280 (≈ 8500m), and FL380 (≈ 11500m), enabled the measurement of ranging performance, which is critical for the achievable navigation performance in terms of accuracy, precision, and integrity largely dependent on the quality of the range estimates.

The measurements obtained relied on the fact that LDACS1 communication system is a cellular network with ground stations separated in frequency and synchronized with each other. This allowed the implementation of an estimation model for the range between the aircraft and station A as follows:

$$r_{est} = r_{true} + C\tau_{HW} + C(\tau_{GS} - \tau_{AIR}) + \varepsilon \qquad \text{(Equation 2)}$$

where r_{est} is the estimated range, r_{true} is the actual (unknown) range, c is the speed of light, τ_{HW} is the delay due to the hardware components in transmitter and receiver, $\tau_{GS} - \tau_{AIR}$ is the clock offset between ground station and the airborne system and ε is a perturbation that accounts for all other errors, such as multipath propagation, tropospheric delays, and white random noise.

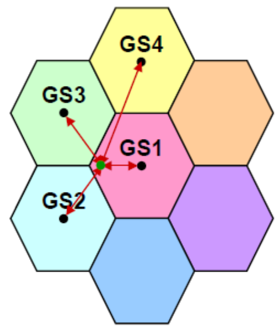


Figure 24 – LDACS1 is a cellular configuration

Any delays due to transmitter and receiver hardware of the measurement system were subject of compensation through an accurate calibration of the measurement equipment. Station A calibration allowed to estimate the transfer function of the whole transmission path including the LDACS1 transmission signal. The resulting calibration signal considers the impact of both the corresponding transmitter and receiver hardware effects and it is recorded when the clocks of both stations are manually aligned in terms of frequency and phase.

The baseband of the calibration signal $C(e^{j\theta})$ is given by:

$$C(e^{j\theta}) = R(e^{j\theta}).T(e^{j\theta}).S(e^{j\theta}) \qquad \text{(Equation 3)}$$

where $S(e^{j\theta})$ is the baseband frequency domain representation of the transmitted LDACS1 signal, and $\mathrm{T}(e^{j\theta})$ and $\mathrm{R}(e^{j\theta})$ are the baseband frequency responses of the transmitter and receiver hardware.

The actual received signal $\mathrm{Y}(e^{j\theta})$ can be represented as:

$$Y(e^{j\theta}) = C(e^{j\theta}).H(e^{j\theta}).E(e^{j\theta}) \qquad \text{(Equation 4)}$$

where $H(e^{j\theta})$ is the baseband frequency that accounts for all other signal delays and $\mathrm{E}(e^{j\theta})$ is the additive measurement noise.

In order to estimate the range the measured received signal $\mathrm{Y}(e^{j\theta})$ was multiplied with a complex conjugated and normalized version of the calibration signal:

$\hat{C}(e^{j\theta}) = C*(e^{j\theta})/|C(e^{j\theta})|^2$ (Equation 5)

In other words, the signal $\mathrm{Y}(e^{j\theta})$ was subject of correlation with the calibration signal.

The estimated amplitude and phase responses for the calibration signal were pre-defined; as well as the clock offset between Station A and the receiver clock.

Assuming that the propagation channel between transmitter and receiver consists purely of a single propagation path (line of sight), the range estimation can be solved by multiplying the received signal $\mathrm{Y}(e^{j\theta})$ with the normalized, complex-conjugate calibration signal $\hat{C}(e^{j\theta})$.

The pseudo range could be estimated, either from the phase of the product $\hat{C}(e^{j\theta})\mathrm{x}\mathrm{Y}(e^{j\theta})$ or by estimating the location of the maximum of its inverse Fourier transform, i.e. finding the location of the maximum correlation peak.

The range estimation results obtained, using the abovementioned correlation principles, for different segments of the flight were the following:

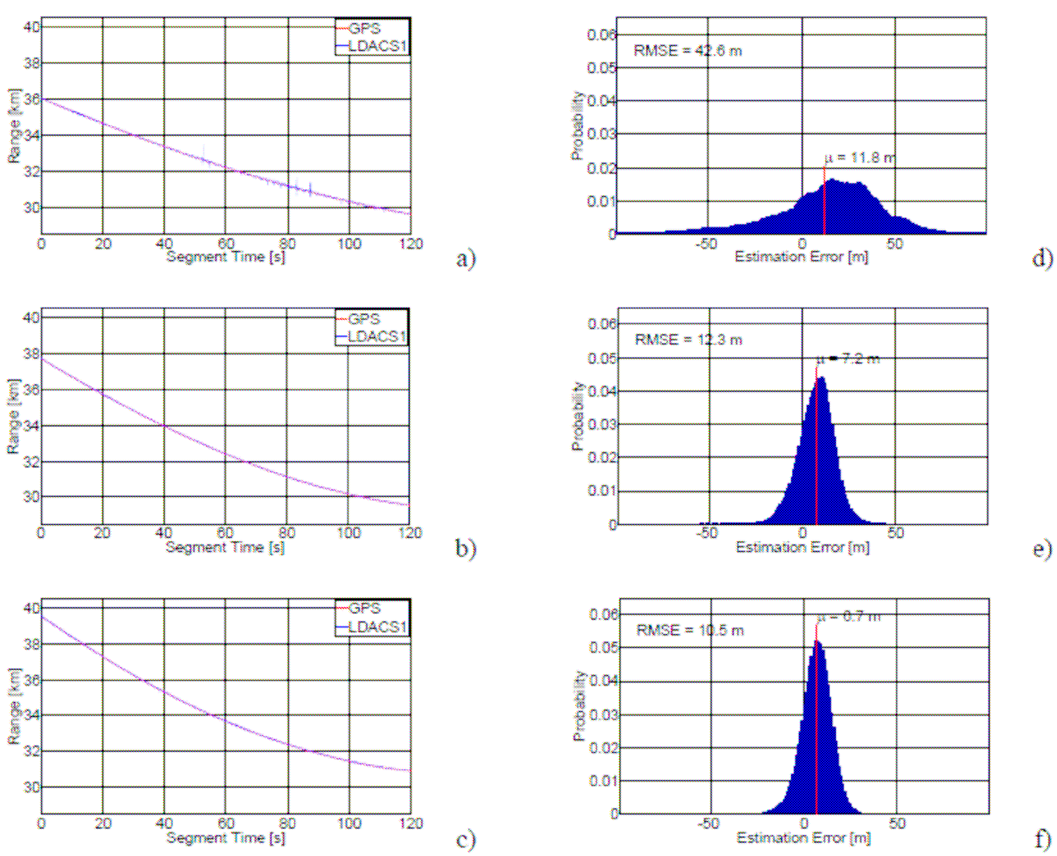


Figure 25 – Estimated ranges and range errors computed for the selected flight segments
(Source [27])

Figure 25 shows the estimated ranges and range errors computed for the selected flight segments for (a,d) FL100, (b,e) FL280, and (c,f) FL380. Graphs (a), (b), and (c) show the estimated range and the range determined from ground truth over time. Graphs (d), (e) and (f) show empirical range error distributions.

The conclusion was that for lower altitudes the range estimation is far worse than for higher altitudes. However, a non-line of sight (non-LOS) case was observed at FL100, resulting in a range error of more than 2000 m. The Root Mean Squared Error (RMSE) for the whole flight is only 15.2 m, with 99 percentile corresponding to only 50 m. The bias of the range estimation is only 6.7 m. Feasibility could not be demonstrated for flight level 100 (10.000 feet). The encountered problems indicate that, for lower flight levels, non-LOS transmissions in a propagation environment with obstacles (Rayleigh) evidence poor ranging accuracies.

In multipath rich environments ranging becomes a challenging problem when used with low bandwidth signals: unless multipath interference is resolved, large ranging errors are typical.

At this stage it is fundamental to recall, from Section 2, that the feasibility target would be

RNP-0.3 implying a lateral accuracy limit of 556.6 m. Due to the above described results for FL100 or below even for this requirement the ranging accuracy could not be demonstrated.

This behaviour might have a bearing on various factors affecting the performance of the range estimator for lower elevation angles namely:

- tropospheric effect that might lead to a higher estimation bias;
- relative position difference between the GPS antenna, which is mounted on the top of the aircraft fuselage, and the LDACS1 receiving antenna, which is located on the bottom (since the antennas are not collocated, the ground truth determined from GPS data depends on the exact roll, pitch and yaw of the airplane);
- interference due to the spectral proximity of the LDACS1 signals to DME;
- multipath effects, which will be considered later in the thesis, significantly impacting the instability of the range estimates at lower altitudes, especially during banking turns.

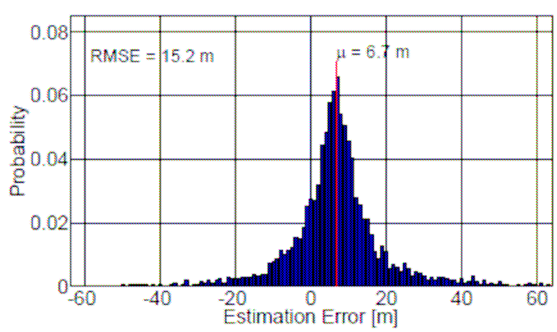


Figure 26 – Range error distribution for the entire flight (higher flight levels)
(Source [27])

A key aspect was that the LDACS prototype used by DLR, described in [27], was still rather embryonic and does not evidence full compliance to all LDACS specifications including advanced channel estimation allowing severe multipath to occur. The tested prototype features only a form of Reed-Solomon (RS) coding and pilot insertion.

Subsequent theoretical work was conducted by DLR addressing the effect of multipath on LDACS1. This work considered a state-of-the-art super-resolution multipath estimation algorithm. That algorithm is based on the so-called “fast variational sparse Bayesian parameter estimation scheme” and a classical Kalman filter and was used for tracking individual multipath components [39] [40].

That algorithm would allow the incremental estimation of the parameters of multipath components, which are the delay and Doppler frequency of each propagation path, as well as automatic estimation of number of components detectable in measurement data. Using Kalman filter the individual propagation paths can be tracked over time.

This tracking algorithm was named Sparse Adaptive Multipath Estimation (SAME) and enabled to follow the GPS range quite closely, mitigating the multipath interference and drastically reducing the range root mean square error (RMSE).

It was decided not to cover that analysis in the present thesis due to its complexity. Nevertheless, it was noted from [39] that one sample equals the distance of about 480m, considering the speed of light in air. LDACS1 symbol consumes 120 µs and one sample takes 1.6 µs. With that it would be possible to associate the range error in terms of distance with the performance in terms of bit (or symbol) error rate (BER).

Instead of the SAME approach, this thesis relies on the statements in the LDACS1 specification [22] where it is prescribed that a target Bit Error Rate (BER) of 10^{-6} must be achieved. This specification says that a BER at that level fulfills the optimal operation of LDACS1 assuming the maximum frequency offset, for the transmission between the GS and the AS as well as maximum AS Doppler shift, relative to the GS, corresponding to the aircraft speed of ± 850 knots[16].

In summary, three LDACS1 improvements will be proposed. One of those will focus on mitigating the effects of multipath/Doppler shift. For that case it is assumed that a BER at 10^{-6}, achieved with improved channel estimation, will guarantee LDACS1 optimal performance including a ranging error far below the required 556.6 meters required for RNP-0.3. This is an important assumption for this work.

This thesis will propose three specific LDACS ranging/position determination improvements based on the military data link example:

- use of Kalman filter to improve position tracking
- multilateration on the basis of air-air transmissions

[16] This assumption is valid when GS is using all FL sub-carriers (Nused = Nu) with QPSK modulation, convolutional coding with rcc = ½, interleaving over 8 FL data frames and Reed-Solomon RS (101,91,5) coding in FL data frames, the airborne LDACS1 RX shall fulfil the reference BER requirement (10^{-6} from the specification) when operating at the sensitivity level S0 ≤ -104.13 dBm.

- a more advanced channel estimation approach.

5.2 USE OF KALMAN FILTER TO IMPROVE POSITION TRACKING

What is a Kalman Filter?

A Kalman filter is an optimal estimator - it infers parameters of interest from indirect, inaccurate and uncertain observations. It is recursive so that new measurements are processed as they arrive. Kalman filtering is used to track the estimated signals after using an algorithm to detect and estimate the individual multipath components. A more extensive description of the features and use of Kalman filters can be found in annex B.

The estimation algorithm offers an incremental estimation of the parameters of the multipath components, namely the delay and Doppler frequency of each propagation path, as well as automatic estimation of the number of components, which can be detected in measurement data.

When applied for the tracking of moving target in space [28], Kalman filter became a standard estimation algorithm extensively used in the development tracking algorithms. Kalman filter would provide minimum mean square error (MMSE) when the measurements are in Cartesian coordinates, measurements are independent & gaussian distribution and target behaviour (i.e. target mathematical model) is known.

The goal of the target tracking system is to form and maintain track on target of interest from the measurements provided by the sensors. Figure 27 shows the information flow diagram of a typical recursive target tracking system. Its basic elements are time prediction and measurement update. First step is to carry out time prediction. Prediction of tracks from the frame uses the target process model. In measurement update, the measurement from frame is incorporated into the predicted state estimate to obtain an improved estimate using measurement model.

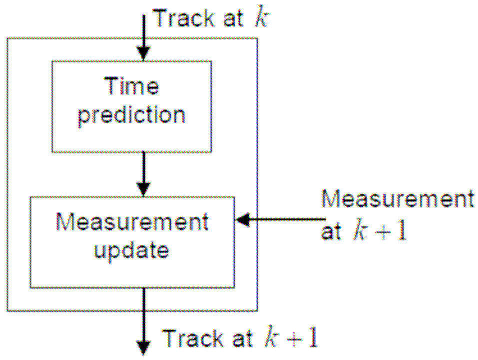


Figure 27 – Information flow diagram of recursive target state estimation

Annex B contains details on the particular model and algorithm implemented by the Kalman filter when used for target state estimation. In conclusion, the aim of the Kalman filter is to combine the measurements taken from the target with the information provided by the motion model in order to obtain an optimal estimate of the target state. Its application as in the case of military relative navigation allows a drastic reduction of the ranging error MMSE.

Simulation

A SIMULINK model ascertains the level of improvement offered when a Kalman filter is associated with LDACS. This model (see Figure 28) generates aircraft position, velocity, and acceleration in polar (range-bearing) coordinates; it adds measurement noise to simulate inaccurate readings by the sensor and uses a Kalman filter to estimate an aircraft's position and velocity from noisy radar measurements.

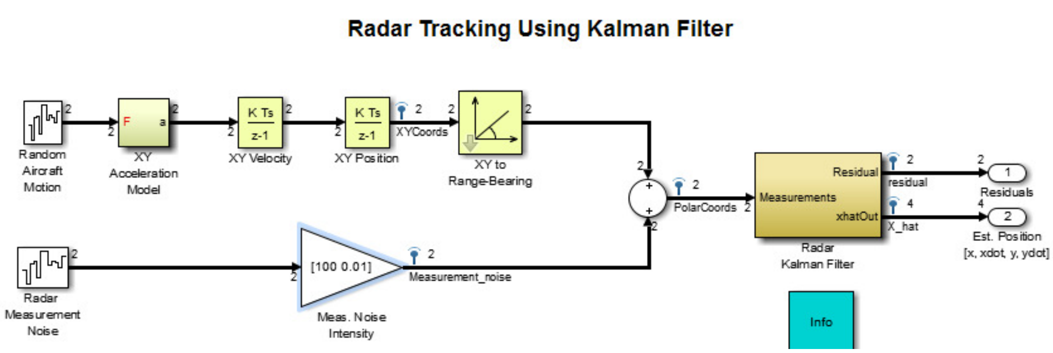


Figure 28 – SIMULINK model

Running the model we obtain

- The actual trajectory compared to the estimated trajectory
- The estimated residual for range

- The actual, measured, and estimated positions in X (North-South) and Y (East-West)

Estimation of the aircraft's position and velocity results from the 'Radar Kalman Filter' subsystem. This subsystem samples the noisy measurements, converts them to rectangular coordinates, and sends them as input to the Kalman Filter block.

The Kalman Filter block produces two outputs in this application. The first is an estimate of the actual position. This output suffers conversion back to polar coordinates so that it can compare with the measurement to produce a residual: the difference between the estimate and the measurement. Kalman Filter smoothes the resulting position data to produce the estimate of the actual position.

Figure 29 shows that the initial range error reduces by the action of the Kalman filter after taking more samples. It goes easily from around 5000 feet to less than 20 feet after 100 measurements. Similarly, it is visible that the position estimated as an output from the Kalman filter becomes very close to the real position.

Higher-precision measurements could result from the correct setting of parameters/initial values like Initial Velocity Mismatch and Measurement Noise.

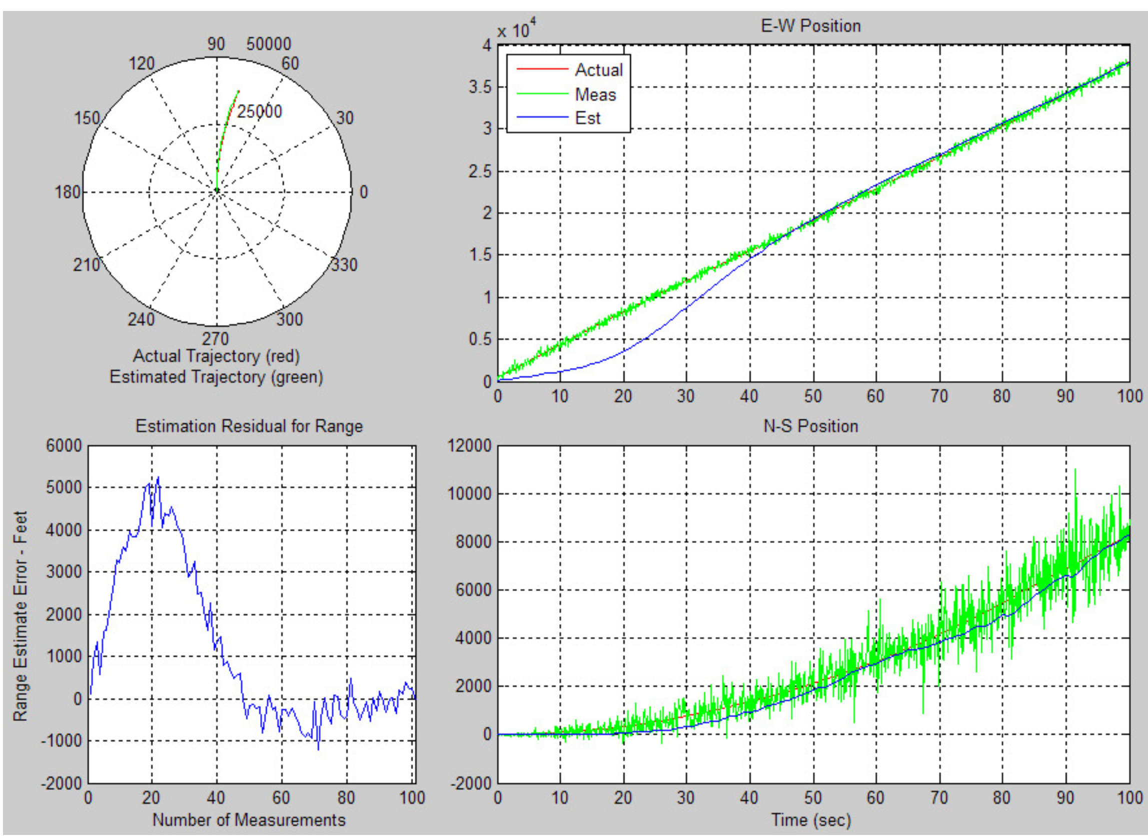


Figure 29 – Simulation results

Kalman filter could add to LDACS configuration, as shown for the military Relative Navigation data link solution described before (see Figure 21).

5.3 MULTILATERATION ON THE BASIS OF AIR-AIR TRANSMISSIONS

LDACS1 System Specification defines an air-air mode to be part of LDACS design. This mode supports direct A/A communications without ground support. The LDACS system shall offer a broadcast A/A surveillance link and an addressed (point-to-point) A/A data link, both with direct air-air connectivity. A/A communications between involved LDACS airborne stations takes place in a decentralized, self-organised way without any need for ground support.

The same specification foresees that LDACS A/A mode uses an OFDM-based PHY layer with different parameters (e.g. sub-carrier spacing) than those specified for air-ground mode. An OFDM based PHY layer is combined with the TDMA based users' access to the shared broadcast channel.

The usage of TDMA, high number of potential users and propagation guard times mandate the usage of A/A data frames that are relatively short compared with frames in the A/G mode. The selected data frame size and OFDM symbol duration lead to the required RF channel bandwidth that is higher than for the A/G mode.

A flexible LDACS A/A protocol has been designed to support the aircraft population within the operational range defined by the physical layer design.

Most A/A transmissions are broadcast as explained before. The LDACS specification envisages also the periodic transmission of management data used to overcome the hidden station problem: simultaneous transmission of two or more nodes which are not directly within each others transmission range, but are both within the transmission range of the victim receiver.

A potential way to improve the ranging performance of LDACS could be to take advantage of air-air broadcast transmissions to share positioning information amongst all platforms. This solution would be similar to the military data link relative navigation functionality described in chapter 4 above.

As for the case of military RELNAV, recurrent exchange of positioning and identification messages (PPLI) could benefit from LDACS A/A mode and support improved position determination. The broadcast nature, the use of TDMA and the periodic transmissions already envisaged for LDACS A/A could facilitate the implementation of PPLI-alike exchanges.

It is important to recall that for military RELNAV each airborne terminal continuously calculates its own position by measuring the Time of Arrival of all received PPLIs messages. This function is often designated "multilateration". As such, RELNAV allows the terminal to calculate an accurate value for the range between itself and another transmitting unit. This very accurate range measurement is possible because of the precise timing the terminal must maintain after achieving synchronisation with the network.

Multilateration of signals Time Difference of Arrival (TDOA) of signals at different receivers to identify the position of the source is a technique that military have already used for several decades. Recently, this technique has become available to civil organisations and, for some years, used in airport surveillance. Nowadays, these same techniques are in operation for larger areas such as En-Route or Approach areas. Those are the so-called Wide Area Multilateration (WAM) systems.

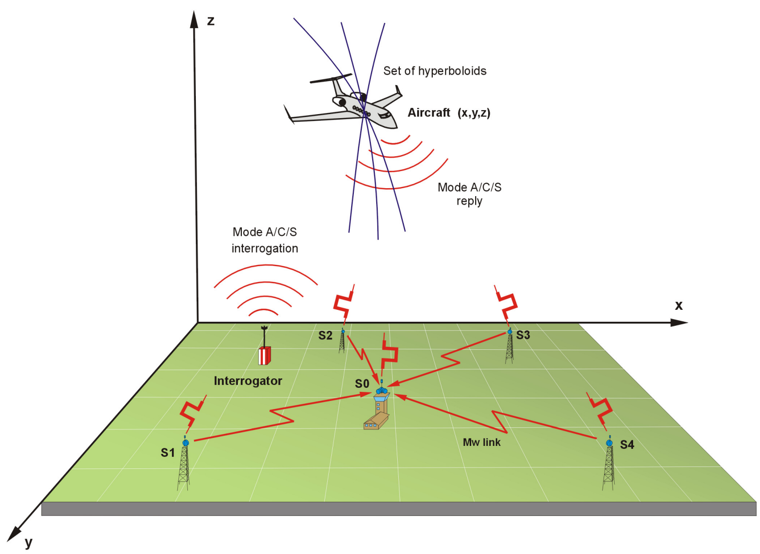


Figure 30 – Multilateration principle
(Source EUROCONTROL)

Multilateration is all about position-determination on the basis of a set of hyperboloids defined after the "triangulation" of signals exchanged between some referenced transceivers (designated as "pseudolites"). For the case of air-air multilateration, the different airborne stations act as those pseudolites.

The set of equations supporting multilateration is depicted in figure 31 below.

$$\tau_L = \frac{1}{c} \cdot \left(\overline{OL} + \overline{LC} - \overline{OC} \right) = f(x, y, z, ...) \qquad \text{(Equation 6)}$$

$$\tau_R = \frac{1}{c} \cdot \left(\overline{OR} + \overline{RC} - \overline{OC} \right) = g(x, y, z, ...) \qquad \text{(Equation 7)}$$

$$\tau_Q = \frac{1}{c} \cdot \left(\overline{OQ} + \overline{QC} - \overline{OC} \right) = h(x, y, z, ...) \qquad \text{(Equation 8)}$$

$$\tau_{L,R,Q} = \text{hyperbolic delays}$$

Figure 31 – Multilateration Equations

If such LDACS A/A multilateration improvement would be implemented the performance gains could be similar to those offered by PPLIs exchanges in military RELNAV: terminal´s position accuracy with a value for position quality (Q_p) indicating that its position uncertainty is up to 50 feet. This calculated value for Q_p would then be shared in PPLI messages supporting estimation of a different value based on different TOAs and Q_p values from the other network units.

LDACS exists only as prototype and industrial research is still underway before a final specification is frozen. Consequently, there is still time to integrate air-air relative navigation in the final system design. The ability for each aircraft to derive its position based on air–air communications with other aircraft in the vicinity, together with the sharing of PPLI messages containing position data, would significantly contribute to overcome the limitations observed in the performance of LDACS air-ground ranging.

5.4 A MORE ADVANCED CHANNEL ESTIMATION APPROACH

Multipath in OFDM Systems

It is important to recall here the assumption made before: LDACS1 improvements target a better ranging performance, mitigating multipath/Doppler shift, but it is assumed that a BER at 10^{-6}, achieved with improved channel estimation, will guarantee LDACS1 optimal performance including a ranging error far below the required 556.6 meters required for RNP-0.3.

As stated before, the original LDACS1 specification requires a Bit Error Rate (BER) of 10^{-6}, or better, after Forward Error Correction. Looking at the results of the DLR trials, it seems likely that this specification feature was not respected by the embryonic LDACS prototype used in those trials. In this section we will perform a simulation to verify the behavior of LDACS

OFDM in terms of BER. The aim will be to improve performance through channel estimation.

LDACS uses OFDM technology with a bandwidth of around 498.5 kHz, relying on 50 subcarriers separated by 9.765625 kHz, the propagation delay is 1.26 ms for 200 NM and for 10 symbols, the Doppler shift is around 1 kHz for a 1080 km/h speed, the guard interval amounts to 4.8 µS with QPSK or QAM as modulation schemes.

OFDM is a transmission technology [29] with an efficient use of the spectrum by allowing overlap of carriers. In other modulation schemes, overlapping adjacent channels can interfere with one another. However, sub-carriers in an OFDM system are orthogonal to one another. Thus, they are able to overlap without interfering because when one signal reaches its maximum peak the adjacent one is zero. As a result, OFDM systems are able to maximize spectral efficiency without causing adjacent channel interference.

In fact, OFDM is a very efficient way to mitigate multipath because in slow time-varying channels capacity can be enhanced by adapting data rate per subcarrier according to signal to noise ratio. Known OFDM drawbacks include sensitivity to frequency offset and large peak-to-average power ratio.

The frequency domain of an OFDM system is represented in the diagram below (Figure 32).

Since the input data stream is divided in subcarriers the symbol duration is larger, which reduces the multipath delay spread, in relation to the symbol time. To eliminate Inter Symbol Interference (ISI) almost completely a guard time is introduced or each OFDM symbol. Should the guard time be larger than the delay spread the multipath components from one symbol will not interfere with the next symbol.

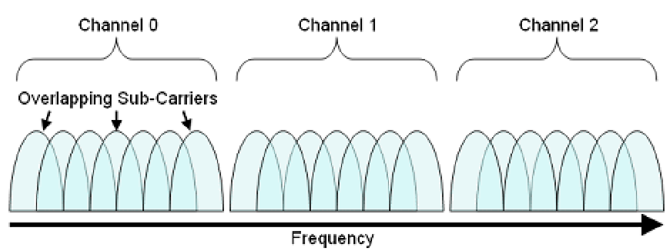


Figure 32 – Frequency domain of an OFDM system

The guard time could consist of no signal at all and, in such situation, the problem of Inter Carrier Interference (ICI) could occur. ICI means crosstalk between adjacent subcarriers with a lost of orthogonality.

To eliminate ICI the symbol is “cyclically extended” in the guard time. The Cyclic Prefix (CP)

[30] (see Figure 33) ensures that the multipath signals with delays smaller than the guard time cannot cause ICI. This is done by ensuring that any delayed replicas of the OFDM symbol have an integer number of cycles within the FFT interval, assuming that the delay is smaller than the guard time.

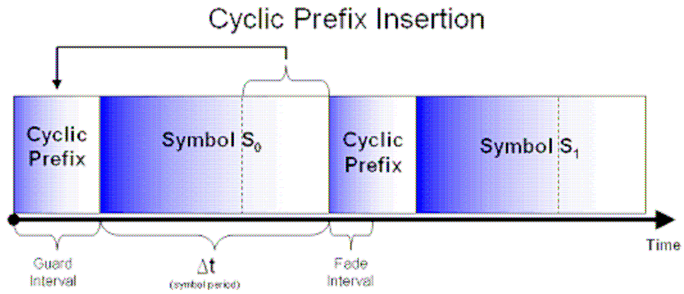


Figure 33 – Cyclic prefix insertion

In summary, in a typical OFDM broadband wireless communication system, a guard interval, using cyclic prefix, shall be inserted to avoid ISI and ICI [31] [32] [33].

This guard interval is required to be at least equal to, or longer than the maximum channel delay spread. This method is very simple, but it reduces the transmission efficiency. Some authors defend that transmission efficiency can be increased through a time domain equalizer to shorten the channel impulse response within the guard interval.

In a channel affected by multipath propagation, the signal interacts with many objects in the environment producing multiple copies of the transmitted signal i.e. multipath signal components. These multipath signals might be attenuated in power, shifted in phase and/or frequency and delayed in time. For this reason when they are all combined at the receiver side, the reconstructed signal is distorted. Indeed, if a single narrow pulse is transmitted the received signal is a pulse train and each component corresponds to a different path. Moreover, In OFDM systems, due to user mobility, each carrier is subject to Doppler shifts resulting in time-varying fading.

This leads to the discussion about the need to ensure coherent detection. OFDM demodulation must be synchronized with the start and end of the transmitted symbol (or bit) period and knowledge is needed about the reference phase and amplitude of the constellation of each subcarrier (affected by random phase shift or and amplitude change due to carrier frequency offset). Coherent detection is the way to cope with such phase and amplitude variations using one of the channel estimation techniques.

Channel estimation models/algorithms shall not create too much training overhead and aim at detecting the reference values that allow the best decision boundaries for the constellation. The channel estimation block of an OFDM receiver determines the reference phase and amplitude for all subcarriers. Out of the multiple channel estimation techniques we decided to choose, for the present work, one based on the use of Kalman filter.

It is a decision-directed channel estimation option that avoids the use of pilots that have a cost in terms of transmitted power. In this case, data estimations are used to remove the data modulation from the received subcarriers after which all subcarriers can be better used to estimate the channel.

Use of Kalman Filter

We have concluded from the DLR trials described before that multipath propagation might be a major factor disturbing the ranging performance at lower flight levels. Mitigating such multipath effects entails the application of:

- a multipath estimation algorithm
- a Kalman filter (as one of the options for channel estimation)
- improved positioning taking advantage of air-air multilateration or other sources

As explained before, time varying frequency selective multipath channels destroy the orthogonality of OFDM subcarrier introducing inter carrier interference. In this thesis we will focus on the use of Kalman filtering to support channel estimation thus mitigating inter carrier interference, caused by multipath effects, in OFDM technology, which is the basis of LDACS.

A time domain Kalman filter can be used [34] to estimate channel impulse response on every sample of OFDM symbol. The estimated coefficients are applied to the equalizer[17] to equalize received OFDM signal.

Training sequence/pilot aided techniques and blind techniques are two basic families for channel estimation. In our case we consider the use of a Kalman filter to perform time-based channel estimation (based on the concept of Minimum Mean Square Error) [35] [36]. In the case of relative navigation implemented in military data links, described before, Kalman filters are used for a different purpose: they can also help to correct trajectories of moving objects.

Figure 34 below depicts a full OFDM transceiver scheme with the channel estimation /

[17] Minimum mean-square error (MMSE) approach which minimizes the sum of ISI and noise.

equalization ensured by the use of Kalman filtering. The OFDM symbols are obtained on the basis of QPSK or QAM modulation followed by the application of Indirect/Direct (Fast) Fourier Transforms, insertion (or not) of cyclic prefix/guard band (and eventually pilot/training symbols), a noisy channel with Rayleigh multipath fading and a number of series/parallel conversions and coding.

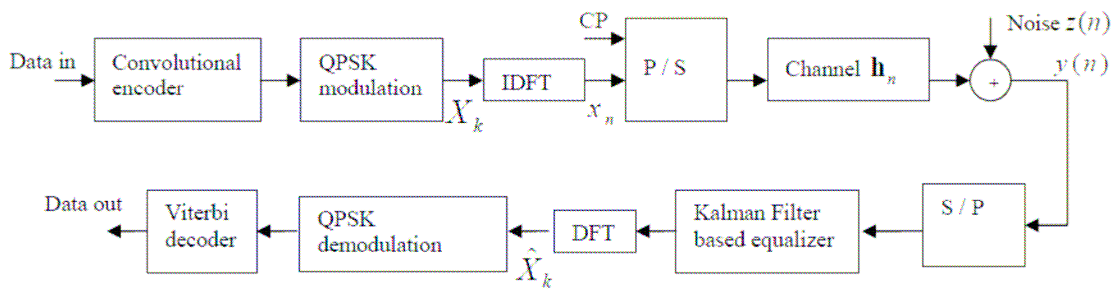


Figure 34 – OFDM scheme 1 with Kalman filter applied

The joint problem of channel estimation and ICI suppression in high mobility OFDM systems can be addressed through the application of a Kalman filter followed by the use of convolutional coding. This method is seen to provide a good performance at high Doppler spreads.

Simulation Results

As stated in the introduction, when the scope was defined, this is not a thesis on OFDM. However, a SIMULINK model (Annex C) was used to evaluate the standard OFDM Bit Error Rate (BER), without channel estimation, based on the parameters applicable to LDACS as recalled before.

Initially we could see some multipath components (Figure 35).

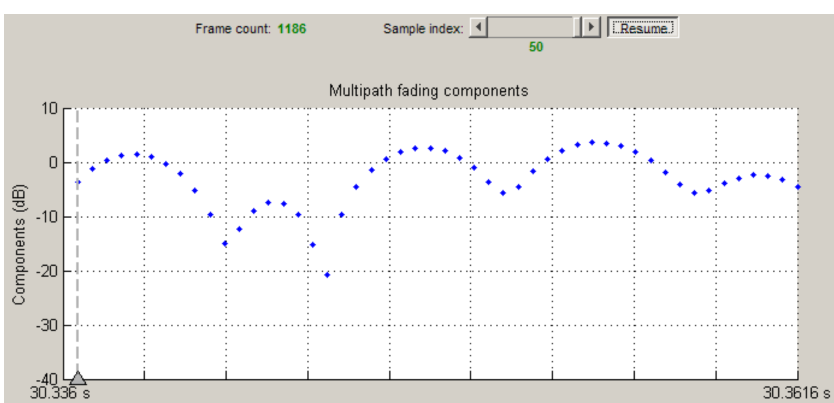


Figure 35 – Multipath fading components

Subsequently, a MATLAB script for time varying channel estimation using Kalman filter (Annex C) was used to identify the level of improvement introduced by channel estimation, for equivalent parameters, which is fundamental to remove ISI/ICI and achieve the required level of synchronization mitigating multipath.

We confirm in this simulation the effect of applying Kalman filtering to channel estimation as described in [38] Fundamentals of Statistical Signal Processing, Volume I: Estimation Theory (v. 1), Steven M. Kay. A Mean Square Error (MSE) of more than 0.2 when estimation is not applied decreases to around 0.02 after 100 samples as soon as Kalman filters are used (see Figures 36 and 37).

After going through several published references (see reference list [34] to [36]) on OFDM channel estimation using Kalman filters, it can be concluded that the order of magnitude of such channel estimation mitigating benefit is always above 10 times and it offers benefits above all other channel estimation techniques.

The channel was defined to include Rayleigh fading, SNR=20 dB, the tolerated Doppler shift was set to 1000 Hz (as for LDACS) and the Doppler spectrum type was Jakes. QPSK constellation was defined with M=4 and a sample rate of Ts=128 µS.

Even if those simulations were very basic, it could be concluded that for a LDACS OFDM channel using QPSK modulation, with a Signal Noise Rate (SNR) until 15 to 20 dB, we obtain a BER between 10^{-2} and 10^{-3} when no channel equalization is used. With channel estimation, the BER moves to the area around 10^{-4} to 10^{-6}. For other modulation schemes the results are similar (see Figures 38 and 39 for QAM standard - without channel estimation – and with Kalman).

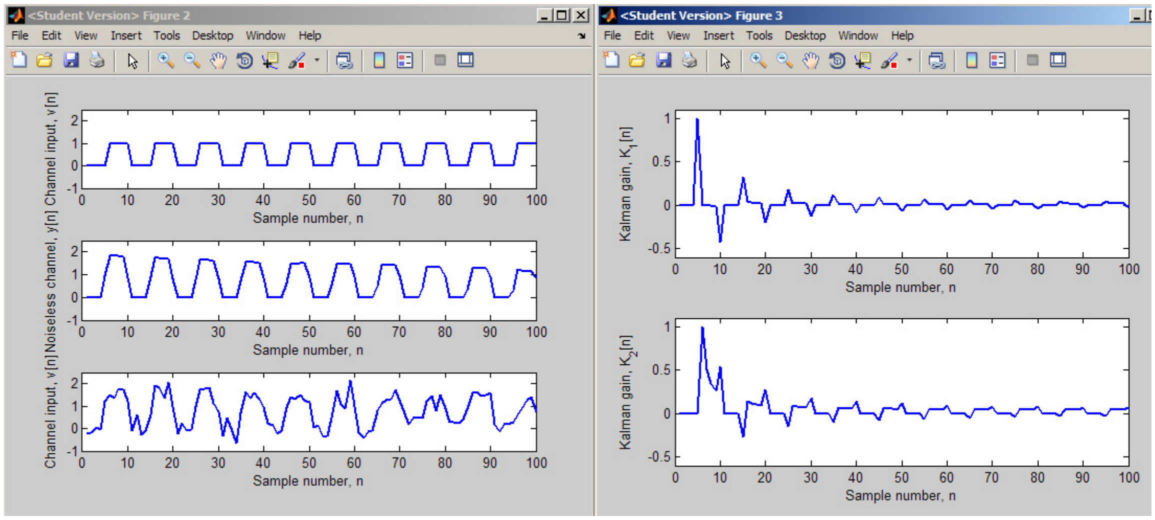


Figure 36 – Kalman filter applied to OFDM channel estimation (1)

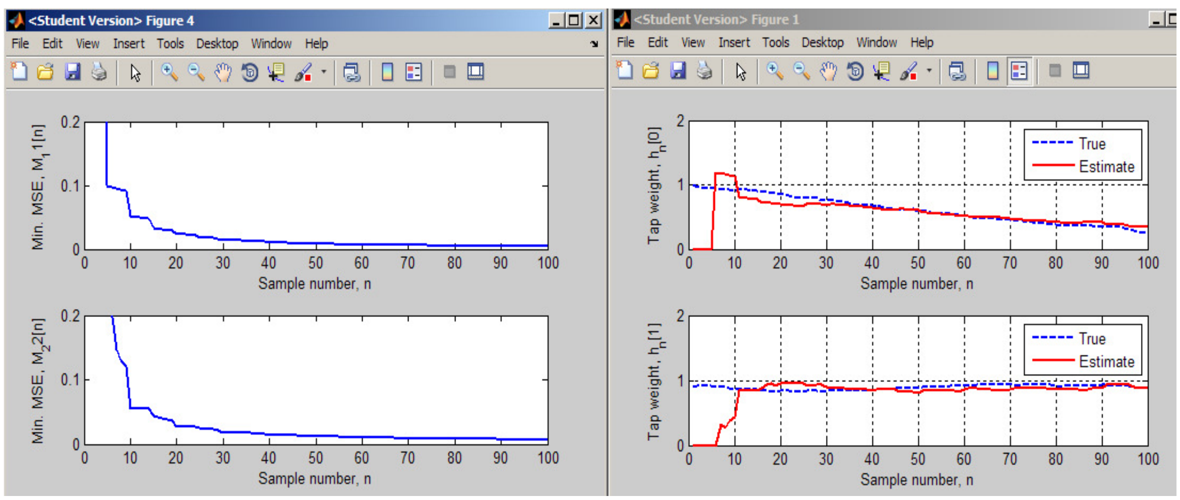


Figure 37 – Kalman filter applied to OFDM channel estimation (2)

Figures 38 and 39 reflect the application of a Kalman Filter improved by implementing a two-stage filter. In first stage the Kalman based statistical analysis is performed to estimate the PAPR and the respective Phase variated PAPR reduction is performed. In the second stage the ICI reduction is performed by implementing the Kalman filter-based carrier offset values.

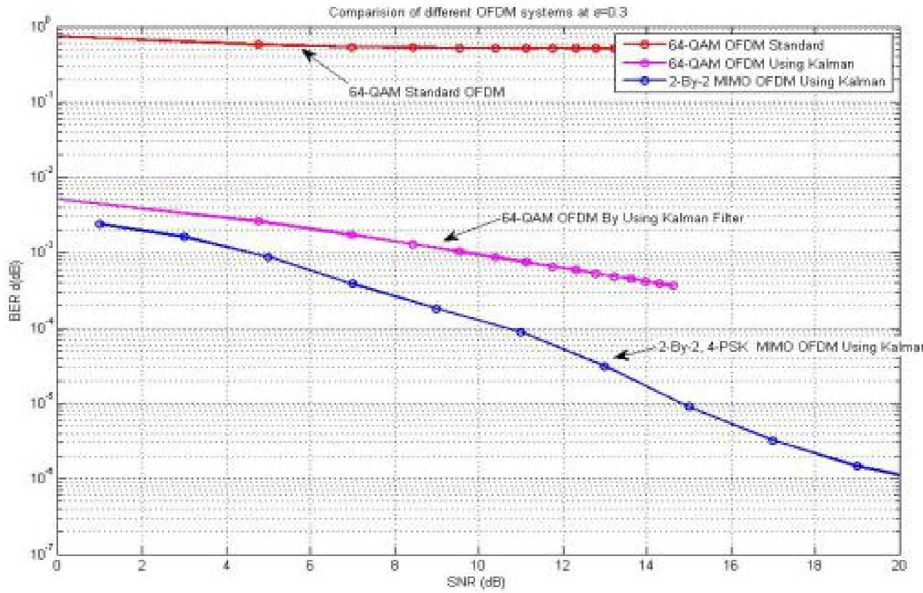


Figure 38 – Comparison of SNR vs BER of different QAM OFDM systems
(Source *http://www.ijritcc.org*)

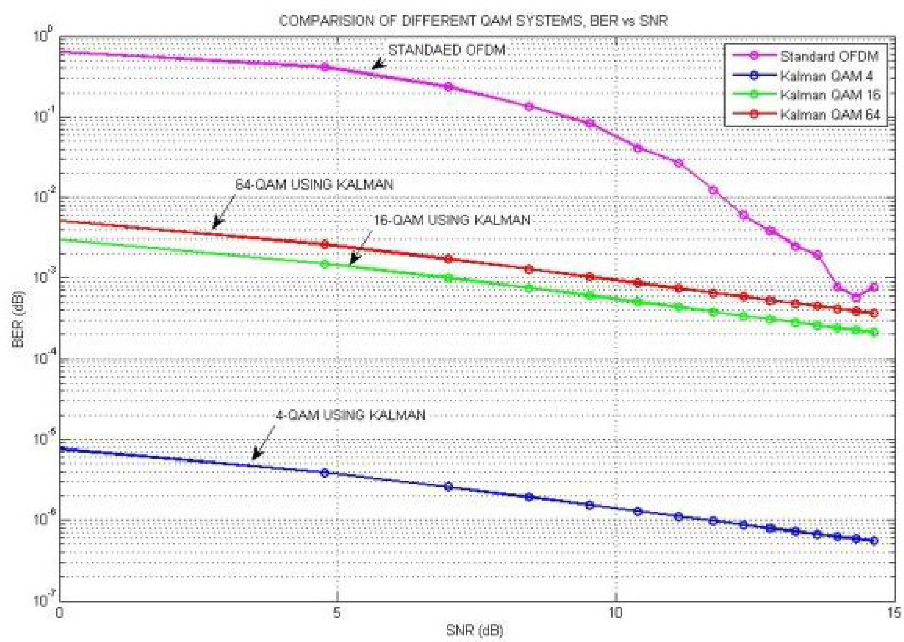


Figure 39 – Comparison of SNR vs BER of different QAM OFDM systems
(Source *http://www.ijritcc.org*)

The interference leads (Figure 39) to a poor signal to noise ratio as well as high bit error rate. The proposed system will improve the signal by removing the different kind of impurities over the signal. These impurities include the ICI, PAPR and the noise over the signal. The signal will be more effective than any standard OFDM.

A Mean Square Error of more than 0.2 when channel estimation is not applied decreases to around 0.02 after 100 samples as soon as Kalman filters are used. As said before, it becomes clear that channel estimation using Kalman filters enables a 10-time enhancement and it offers benefits above all other channel estimation techniques. With that approach the specification BER value of 10^{-6} can be eventually within reach.

Again, this LDACS improvement seems suitable for a future final specification to mitigate decisively the inconvenient generated by higher multipath levels.

6 CONCLUSIONS

6.1 SUMMARY OF RESULTS

Future aeronautical navigation requirements will rely mainly on GNSS satellite infrastructure and its augmentation systems. However, GNSS vulnerabilities including jamming, solar events or other outages dictate the need to keep a ground based back up to guarantee the service continuity. Current navigation infrastructure rationalisation plans indicate that existing Distance Measuring Equipment will be in operation to ensure the aforementioned navigation back up to GNSS.

Existing European DME infrastructure evidences significant coverage limitations in particular at lower flight levels. In addition, DMEs are “paired” with other NAVAIDS (VOR, ILS, etc.) and its integrity levels might be insufficient to fulfil the requirements of advanced navigation concepts, namely the more demanding specifications defined under the framework of ICAO Performance Based Navigation.

The main PBN specifications planned for the European airspace include various levels of RNAV or RNP. DME/DME positioning may not support RNP-0.3 navigation specifications that require on-board performance monitoring and failure alerting. The high level goal of OPMA is to achieve a bound on Total System Error at a 10^{-5} per flight hour integrity risk level. Integrity target would be to sustain defined levels of RNP (e.g 0.3 NM = 556.6 meters), including OPMA.

To overcome the limitations of existing DME infrastructure to be seen as an effective GNSS back up and to alleviate the spectrum congestion in the band 960 to 1200 MHz research is ongoing to identify a means of Alternative Positioning Navigation and Timing. The reutilization of future air-ground data links (e.g LDACS) is seen as one of the most promising options.

LDACS will be implemented anyway as an evolution of today´s air-ground data links (e.g VDL Mode 2), used to support controller-pilot data link communications, as well as to enable advanced aeronautical communications requirements. LDACS rely on OFDM technology. To verify its suitability to be used concomitantly as A-PNT an LDACS prototype was submitted to flight trials conducted under the aegis of DLR (the German Aerospace Center).

Those trials concluded that, for lower altitudes, the range performance is quite bad as a non-line of sight (NLOS) case was observed at FL100 (10.000 feet), which resulted in a range error of more than 2000 meters. Performances at higher altitudes were satisfactory: the Root Mean Squared Error for the whole flight was 15.2 m, with 99 percentile corresponding to 50 m. The bias of the range estimation is only 6.7 m. In a propagation environment with obstacles (Rayleigh) and for lower flight levels, LDACS NLOS transmissions evidence poor ranging accuracies. DLR did progress some follow up work to mitigate multipath through advanced Bayesian algorithms but that work was not yet conclusive and was not pursued in this thesis.

For LDACS to be considered as a feasible system for A-PNT it is imperative to identify areas for improvement so that the ranging/positioning accuracy satisfies the identified targets for PBN.

In the military context, a TDMA air-ground data link (JTIDS/MIDS Link 16) is operational for relative navigation. RELNAV is an automatic function of the Link 16 terminal, used to determine the distance between platforms by measuring the arrival times of transmissions and correlating them with reported positions.

RELNAV data improves unit's positional accuracy. If two or more units have accurate and independent knowledge of their geodetic positions, RELNAV can provide all units of the network with accurate geodetic positions. As a result, the precise geodetic position of every unit can be permanently available at every other unit.

Each airborne terminal continuously calculates its own position by measuring the Times of Arrival of all received Precise Participant Location Information messages. As such, RELNAV allows the terminal to calculate an accurate value for the range between itself and another Link 16 transmitting unit. This very accurate range measurement is possible because of the precise timing the terminal must maintain after achieving synchronisation with the network.

Military RELNAV strongly relies on the air-air communications capability of Link 16, allowing the exchange of the recurrent PPLI messages, and on the use of a Kalman filter to compute position and velocity solutions in two separate grids, the relative grid (REL GRID - u,v,w) and the geodetic grid (GEO GRID - latitude, longitude, altitude).

Receiving PPLIs from additional units further contributes to the terminal´s position accuracy. The value for Position Quality (Q_p) can range from 0 (indicating that its position uncertainty is greater than 18.080 feet) to 15 (indicating that its position uncertainty is within 50 feet). The terminal will then transmit this calculated value for Q_p in its own PPLI – until it calculates a different value based on different TOAs and Q_p values from the other network units from which it receives messages.

The ranging/positioning improvements proposed for LDACS include the two main features used in military RELNAV: exchange of recurrent PPLI messages and TOA estimation based on air-air exchanges and the use of a Kalman filter for position estimation. On top of that, an approach based on the use of advanced channel estimation is proposed to mitigate the harmful effect of OFDM multipath propagation and resulting inter carrier interference.

The first improvement would be implemented taking advantage of LDACS A/A broadcast transmissions. As the LDACS specification envisages already the periodic transmission of management data, it can be assumed that the recurrent exchange of PPLI messages and TDOA estimation could be implemented offering a range performance improved up to the indication of position uncertainty is within 50 feet.

The second improvement, the use of a Kalman filter for position estimation, had the objective to improve the ability to track a moving target in space. Kalman filter will provide minimum mean square error when the measurements are in Cartesian coordinates.

A simulation using a SIMULINK model estimated the aircraft's position and velocity, derived from a Kalman Filter subsystem. The result was a reduction of the initial range error by the action of the Kalman filter in the sequence of a number of samples taken. That range error decreased from around 5000 feet to less than 20 feet after 100 measurement samples. End conclusion was that the position estimated as an output from the Kalman filter becomes very close to the real position.

Finally, an improvement to the OFDM configuration selected for LDACS was analysed also using SIMULINK and MATLAB model/script. The objective was to mitigate multipath problems and improve BER performance through the use of Kalman filter to perform channel estimation.

This improvement relies in an important assumption which is that a BER at 10^{-6}, achieved with improved channel estimation, will guarantee LDACS1 optimal performance including a ranging error far below the required 556.6 meters required for RNP-0.3 mitigating multipath/Doppler shift.

The basic simulations performed gave the indication that an LDACS OFDM channel using

QPSK modulation with a SNR until 20 dB triggers a BER between 10^{-2} and 10^{-3} when no channel equalization is used. These are really bad BER results. With channel estimation, the BER moves to the area around 10^{-4} to 10^{-6}. For other modulation schemes the results are similar.

A Minimum Mean Square Error (MMSE) of more than 0.2 when channel estimation is not applied decreases to around 0.02 after 100 samples as soon as Kalman filters are used. This shows that the order of magnitude of such channel estimation using Kalman filters is always above 10 times. With that approach, the LDACS specification BER value of 10^{-6} could eventually be within reach.

It was clear that the LDACS prototype used in DLR trials did not meet the 10^{-6} BER level and that improvements are necessary. Channel estimation based on Kalman filters could provide such level of enhancement and mitigate decisively the inconvenient generated by higher multipath levels, Doppler effects and ICI.

6.2 IMPACT ON NAVIGATION INFRASTRUCTURE RATIONALIZATION

The abovementioned improvements can still be incorporated in future LDACS specifications. LDACS as a future aeronautical communications data link is still being subject of industry research efforts in the context of ICAO and in SESAR industry research projects in Europe. No final aviation standard is in place yet at the level of EUROCAE, RTCA or ICAO. With the proposed improvements, LDACS would be an optimal candidate for A-PNT supporting PBN navigation requirements up to the level of RNP 0.3.

The introduction of a feasible A-PNT system, compliant with PBN requirements, will be fundamental to enable advanced navigation specifications that rely on satellite based (and augmentations) signals together with the availability of a reversionary back up to mitigate GNSS outages. That A-PNT alternative will satisfy RNP requirements including appropriate ranging performance, integrity and alerting in accordance with the needs of the navigation specifications for the European airspace.

The proposed A-PNT alternative will take advantage of a data link infrastructure, already planned, to fulfil air-ground communications requirements. Consequently, at least the airborne equipage will be available and only the ground service provision needs still to be deployed.

Those communications requirements comprise CPDLC and Trajectory Management applications that can co-exist with the proposed navigation functions. In parallel, the use of LDACS as A-PNT will allow the gradual decommissioning of multiple DMEs with the spectrum and economic gains associated.

A 2006 study on the Fragmentation of European ATM conducted by the EUROCONTROL [37] indicated that the cost of duplicated and non-rationalised Communications Navigation and Surveillance (CNS) infrastructure represents something around 20% to 30% of annual cost. This represents an amount between 900 to 1.400 million euros/year but these figures referred to 2006 and did never see any update.

The same study identifies the costs that can be attached to the navigation infrastructure that are rather low (10% of the total) when considering surveillance (radars) and ATC center systems. Nevertheless, the author believes that the direct savings of rationalizing the DME infrastructure, at current prices, will involve several hundreds of million euros/year with a much higher amount associated to economies of scale and indirect impact on a more seamless infrastructure (e.g. avionics) and reduced controller workload.

6.3 SYNERGIES / WAY AHEAD

The present proposals could be relevant in the context of ongoing SESAR research projects, sponsored by the European Commission, where DLR and other industry partners are relevant contributors.

The EUROCONTROL organization, where the author of this thesis has his present assignment, is also a relevant SESAR partner. Nevertheless, the development of this text pursued only academic purposes, on an individual basis and without any link with his EUROCONTROL duties.

In any case, there are significant ongoing discussions about A-PNT and the vulnerabilities associated with the use of GNSS and introduction of PBN in several ICAO groups, panels and other working groups where all options can have a progress towards defragmentation of aviation infrastructure with safety and economic gains.

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ANNEX A - PBN APPLICATIONS - EXAMPLE

Airspace applications that can be developped include for example:

Lateral navigation

a. Closer route spacing, particularly in the en-route;

b. Maintaining same spacing between routes on straight and turning segments without a need to increase route spacing on the turn*;

c. Reduction of the size of the holding area to permit holds to be placed closer together or in more optimum locations;

d. Aircraft ability to comply with tactical parallel offset instructions as an alternative to radar vectoring;

e. Means of enabling curved approaches, particularly through terrain rich areas but also to support environmental mitigation.* Note: Repeatable and predictable turn performance is the basic operational requirement.

Longitudinal navigation

f. Some means to enable the metering of traffic from en-route into terminal airspace;

Vertical navigation

g. Effective management of vertical windows to segregate arrival and departure flows (example in diagram)

h. Effective use of CDOs and CCOs (again for environmental mitigation);

The above requirements serve various benefits: capacity, flight and ATM system efficiency (particularly requirements b, c, e, f and h), airport access (requirement e), enhanced system and sequencing predictability (requirements b and f) etc.

Figure 40 depicts a PBN application example.

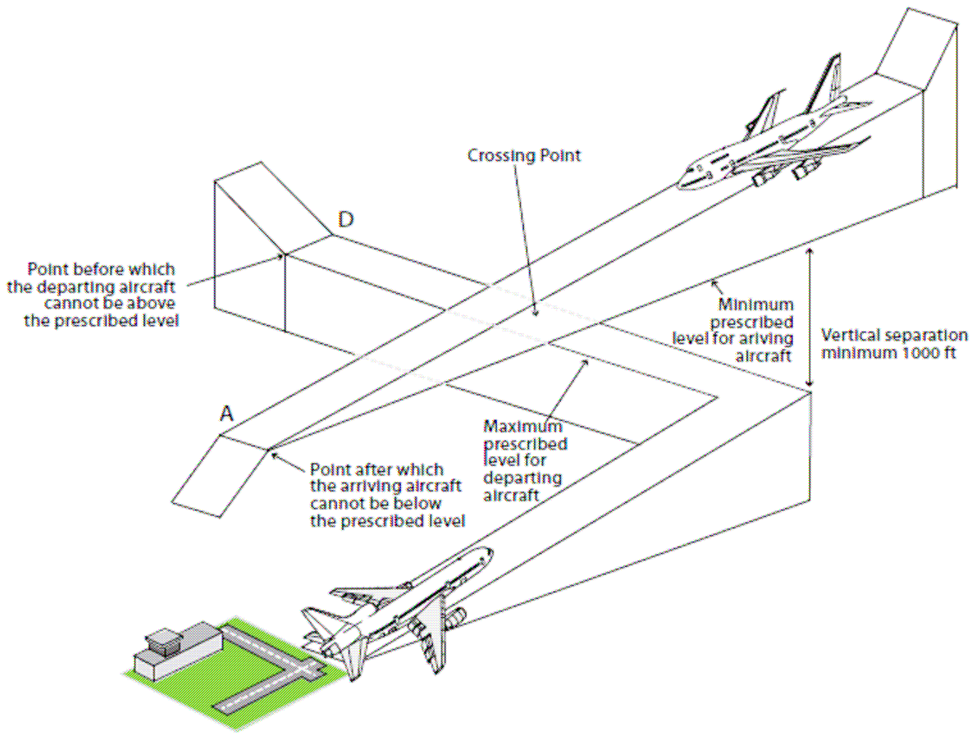

Figure 40 – PBN application
(Source EUROCONTROL)

ANNEX B - KALMAN FILTERS

Kalman filtering, also known as Linear Quadratic Estimation (LQE), is an algorithm that uses a series of measurements observed over time, containing noise (random variations) and other inaccuracies, and produces estimates of unknown variables that tend to be more precise than those based on a single measurement alone. More formally, the Kalman filter operates recursively on streams of noisy input data to produce a statistically optimal estimate of the underlying system state.

The Kalman filter has numerous applications in technology. A common application is for guidance, navigation and control of vehicles, particularly aircraft and spacecraft. Furthermore, the Kalman filter is a widely applied concept in time series analysis used in fields such as signal processing.

The algorithm works in a two-step process. In the prediction step, the Kalman filter produces estimates of the current state variables, along with their uncertainties. Once the outcome of the next measurement (necessarily corrupted with some amount of error, including random noise) is observed, these estimates are updated using a weighted average, with more weight being given to estimates with higher certainty. Because of the algorithm's recursive nature, it can run in real time using only the present input measurements and the previously calculated state and its uncertainty matrix; no additional past information is required.

Extensions and generalizations to the method have also been developed, such as the extended Kalman filter. The underlying model is a Bayesian model similar to a hidden Markov model but where the state space of the latent variables is continuous and where all latent and observed variables have Gaussian distributions.

All measurements and calculations based on models are estimates to some degree. Noisy sensor data, approximations in the equations that describe how a system changes, and external factors that are not accounted for introduce some uncertainty about the inferred values for a system's state. The Kalman filter averages a prediction of a system's state with a new measurement using a weighted average. The purpose of the weights is that values with better (i.e. smaller) estimated uncertainty are "trusted" more. The weights are calculated from the covariance, a measure of the estimated uncertainty of the prediction of the system's state. The result of the weighted average is a new state estimate that lies between the predicted and measured state, and has a better estimated uncertainty than either alone. This process is repeated every time step, with the new estimate and its covariance informing the prediction used in the following iteration. This means that the Kalman filter works recursively and requires only the last "best guess", rather than the entire history, of a system's state to calculate a new state.

Because the certainty of the measurements is often difficult to measure precisely, it is common to discuss the filter's behavior in terms of gain. The Kalman gain is a function of the relative certainty of the measurements and current state estimate, and can be "tuned" to achieve particular performance. With a high gain, the filter places more weight on the measurements, and thus follows them more closely. With a low gain, the filter follows the model predictions more closely, smoothing out noise but decreasing the responsiveness. At the extremes, a gain of one causes the filter to ignore the state estimate entirely, while a gain of zero causes the measurements to be ignored.

When performing the actual calculations for the filter (as discussed below), the state estimate and covariances are coded into matrices to handle the multiple dimensions involved in a single set of calculations. This allows for representation of linear relationships between different state variables (such as position, velocity, and acceleration) in any of the transition models or covariances.

Other authors say that Kalman Filters are a form of predictor-corrector used extensively in control systems engineering for estimating unmeasured states of a process. The estimated states may then be used as part of a strategy for control law design.

It's nearly impossible to grasp the full meaning of Kalman Filter by starting from definitions and complicated equations. For most cases, the state matrices drop out and we obtain the below equation, which is much easier to start with.

current estimation — measured value

$$\hat{X}_k = K_k \cdot Z_k + (1 - K_k) \cdot \hat{X}_{k-1} \qquad \text{(Equation 9)}$$

Kalman Gain — previous estimation

Remember, the k's on the subscript are states. Here we can treat it as discrete time intervals, such as k=1 means 1ms, k=2 means 2ms.

Our purpose is to find $\hat{X}_k$, the estimate of the signal x**.** And we wish to find it for each consequent k's.

Also here, Z_k is the measurement value. Keep in mind that, we are not perfectly sure of these values. Otherwise, we won't be needing to do all these. And K_k is called "**Kalman Gain**" (which is the key point of all these), and $\hat{X}_k - 1$ is the estimate of the signal on the previous state.

The only unknown component in this equation is the Kalman Gain K_k. Because, we have the measurement values, and we already have the previous estimated signal. You should calculate this Kalman Gain for each consequent state. This is not easy of course, but we have all the tools to do it.

On the other hand, let's assume K_k to be 0.5, what do we get? It's a simple averaging! In other words, we should find smarter K_k coefficients at each state. The bottom line is:

Kalman filter finds the most optimum averaging factor for each consequent state. Also somehow remembers a little bit about the past states.

The below graph (Figure 41) illustrates the estimates obtained with a kalman filter on the basis of estimates and measurement.

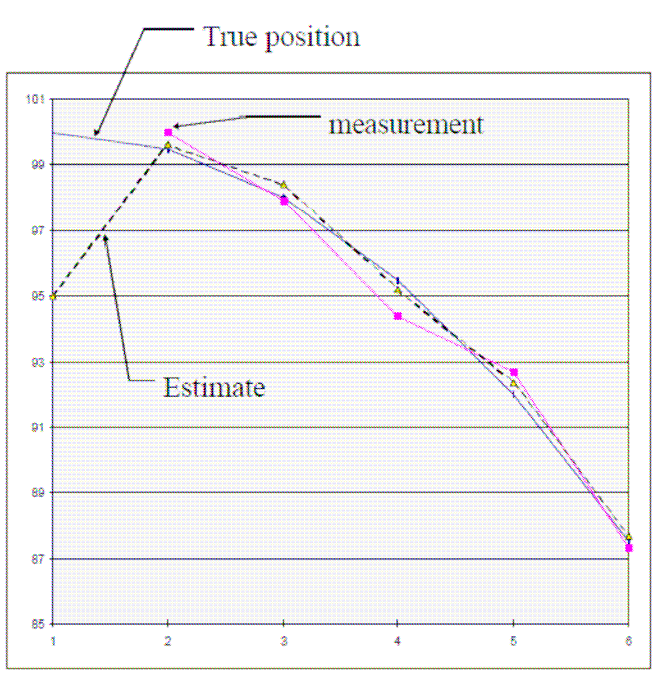

Figure 41 – Result from Kalman Filter application

When a Kalman filter is used for target state estimation the process can be described as follows:

- Kalman filter estimates the states of the target using the process and measurement models
- Two estimates of the state are distinguished: a conditional estimate conditioned on the measurement history up to the current time and an estimate conditioned on the measurement history up through the previous sample time
- There is an estimated state derived from the previous estimation and is known as predicted state obtained from the process model with the time update
- The target state estimation using the Kalman filter is shown in Figure 42. The predicted state and the current measurement are combined by the Kalman filter to get the current estimated state.

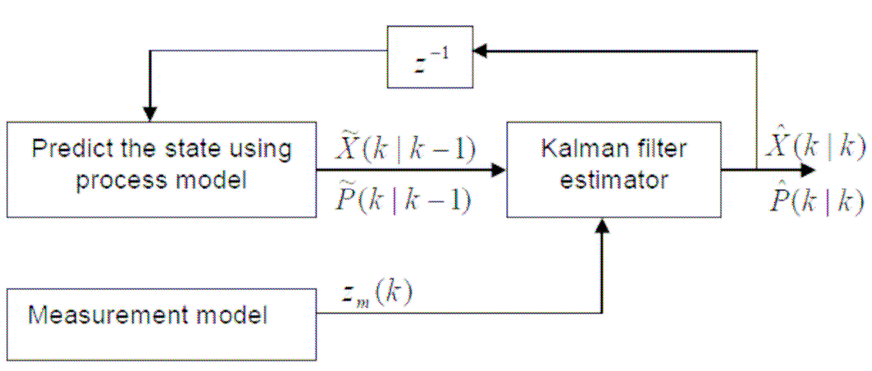

Figure 42 – Estimation process

Additional details on Kalman filters can be found at:

http://bilgin.esme.org/BitsBytes/KalmanFilterforDummies.aspx

ANNEX C - SIMULATION

A QPSK modulation scheme was implemented with the parameters configured in accordance with those of LDACS specification. A SIMULINK model (Figure 43) of a very basic OFDM transceiver was used without channel estimation or any other ICI/ISI mitigating measure (pilots, traning bits, etc.).

The channel was defined to include Rayleigh fading, SNR=20 dB, the tolerated Doppler shift was set to 1000 Hz (as for LDACS) and the Doppler spectrum type was Jakes. QPSK constellation was defined with M=4 and a sample rate of Ts=128 µS.

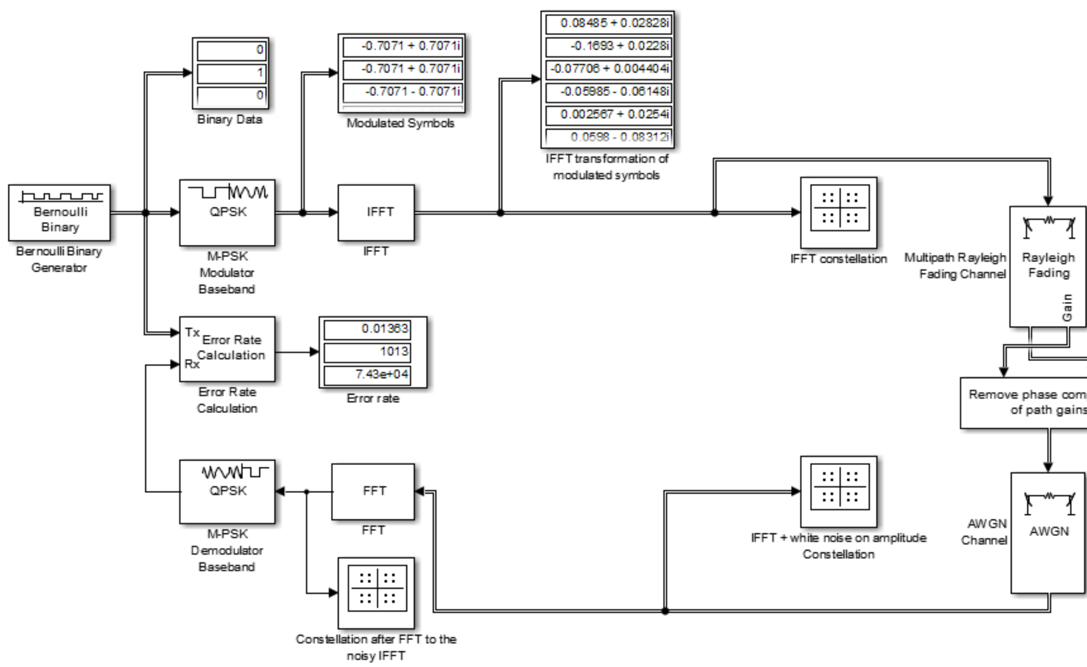

Figure 43 – Simulink Model for a basic OFDM Transceiver

Figure 44 below shows the OFDM constellations contained in the various steps of this simulation.

We have seen that the BER remains poor in the area of 10^{-2} (around 0.013). We have simulated for M=16 and we did obtain BER=0.015. For different parameters and modulation schemes the error rate remains closer.

The objective of the simulation was to ascertain the level of bit error rate associated with the LDACS OFDM transceiver introduced by a dispersive fading Rayleigh channel with multipath.

The next step was to verify the improvement to be offered by channel estimation using a Kalman filter.

For that purpose, a MATLAB script simulating the Kalman channel estimation for OFDM (see it at the end of this annex) was run also on the basis of LDACS parameters. Two parallel filters were used. The results are depicted in Figures 41 and 42.

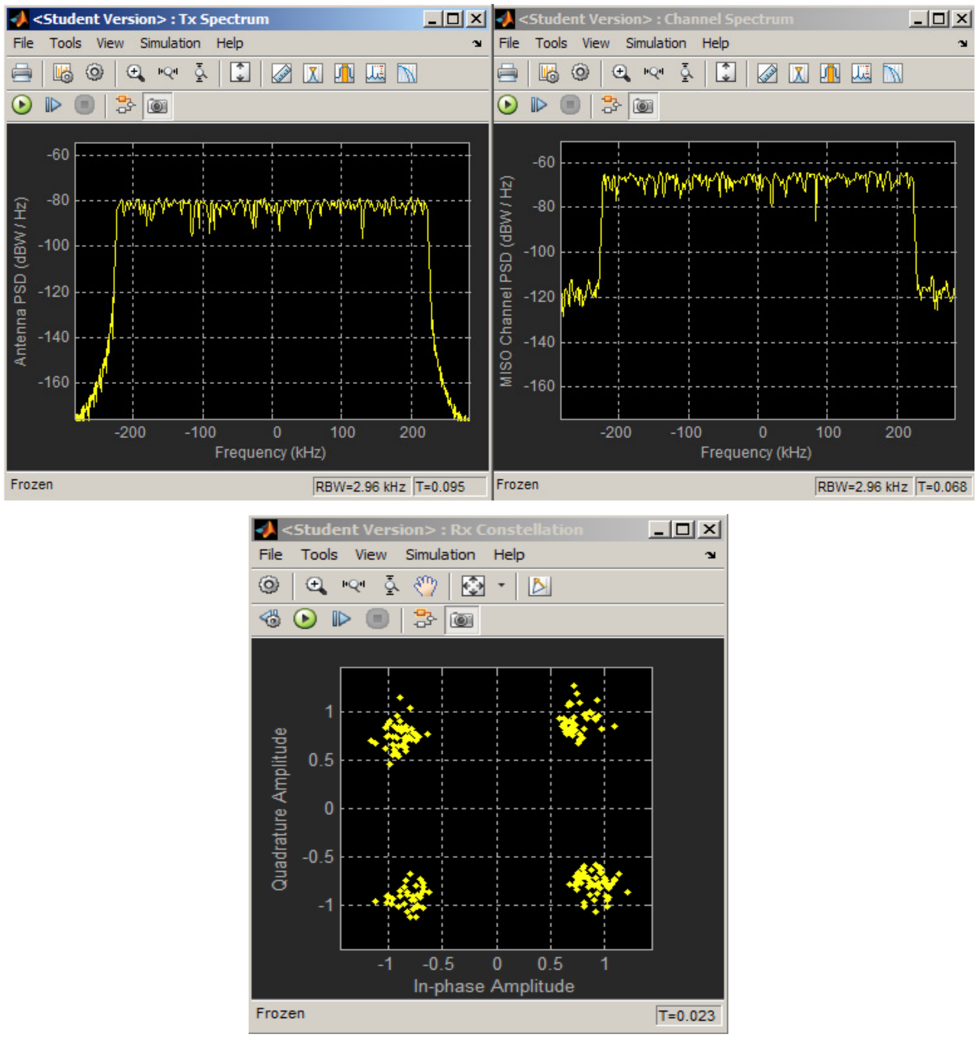

Figure 44 – Spectrum and OFDM Constelation

<u>Matlab script simulating the Kalman channel estimation for OFDM</u>

```
% File Name : main_Kalman_CE.m
% Description: Time varying channel estimation using Kalman filter
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %

clear all;
close all;

% % % % % % % % % % % % Parameter Define % % % % % % % % % % % %
N = 101; % number of observation
p = 2; % number of multipath
A = [0.99 0; 0 0.999];
```

```
sigma_u = 0.01;
Q = [sigma_u^2 0; 0 sigma_u^2];
sigma = sqrt(0.1); % observation noise S.D

H = [1; .9]; % h[-1]
h_hat_1 = [0; 0]; % initial channel state, h_hat[-1|-1]
M_1 = 100*eye(p); % initial MMSE val, M[-1|-1]

w = sigma*randn;
v = [zeros(5,1); ones(5,1);zeros(5,1); ones(5,1)];
v = [v;v;v;v;v;v]; % channel input, v[n]
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h_mat_True = zeros(p,N);
h_mat_Est= zeros(p,N);
K_mat= zeros(p,N);
M_mat= zeros(p,N);
x_free_vec = zeros(1,N);
x_vec= zeros(1,N);

for n = 1 : N-1

U = sigma_u*randn(p,1);
H = A*H+U; % unknown channel update
V = [ v(n+1);v(n) ]; % known input
w = sigma*randn; % wgn
x_free = V'*H ; % Noiseless channel output
x = x_free + w; % Channel Output

h_hat_2 = A*h_hat_1;
M_2 = A*M_1*A'+Q;
K = ( M_2*V )./ ( sigma^2 + V'*M_2*V );
h_hat_1 = h_hat_2 + K*(x -V'*h_hat_2 );
M_1 = ( eye(p) - K*V' )*M_2;

%%% for plotting %%%
x_vec(n) = x;
x_free_vec(n) = x_free;

h_mat_True(:,n) = H;
h_mat_Est(:,n) = h_hat_2;

K_mat(:,n) = K;

M_mat(:,n) = [ M_1(1,1); M_1(2,2) ];

end

figure(1); %title('Realization of TDL coefficients');
subplot(2,1,1);
plot(h_mat_True(1,1:100), '--', 'LineWidth', 2);
hold on; grid on;
plot(h_mat_Est(1,1:100),'r', 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Tap weight, h_n[0]');
legend('True','Estimate');
ylim( [0 2] )

subplot(2,1,2);
plot(h_mat_True(2,1:100), '--', 'LineWidth', 2);
hold on; grid on;
plot(h_mat_Est(2,1:100), 'r', 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Tap weight, h_n[1]');
legend('True','Estimate');
ylim( [0 2] )

figure(2);
subplot(3,1,1);
```

```
plot(v(1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Channel input, v[n]');
ylim( [-1 2.5] )

subplot(3,1,2);
plot(x_free_vec(1,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Noiseless channel, y[n]');
ylim( [-1 2.5] )

subplot(3,1,3);
plot(x_vec(1,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Channel input, v[n]');
ylim( [-1 2.5] )


figure(3);
subplot(2,1,1);
plot(K_mat(1,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Kalman gain, K_1[n]');
ylim( [-.6 1.1] )

subplot(2,1,2);
plot(K_mat(2,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Kalman gain, K_2[n]');
ylim( [-.6 1.1] )


figure(4)
subplot(2,1,1);
plot(M_mat(1,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Min. MSE, M_11[n]');
ylim( [0 0.2] )

subplot(2,1,2);
plot(M_mat(2,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Min. MSE, M_22[n]');
ylim( [0 0.2] )

EDU>>
EDU>> % File Name : main_Kalman_CE.m
% Description: Time varying channel estimation using Kalman filter
%
% Date : 2009.8.3. (by chano.)
%
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %

clear all;
close all;

% % % % % % % % % % % % Parameter Define % % % % % % % % % % % %
N = 101; % number of observation
p = 2; % number of multipath
A = [0.99 0; 0 0.999];
sigma_u = 0.01;
Q = [sigma_u^2 0; 0 sigma_u^2];
sigma = sqrt(0.1); % observation noise S.D

H = [1; .9]; % h[-1]
h_hat_1 = [0; 0]; % initial channel state, h_hat[-1|-1]
M_1 = 100*eye(p); % initial MMSE val, M[-1|-1]

w = sigma*randn;
```

```
v = [zeros(5,1); ones(5,1);zeros(5,1); ones(5,1)];
v = [v;v;v;v;v;v]; % channel input, v[n]
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h_mat_True = zeros(p,N);
h_mat_Est= zeros(p,N);
K_mat= zeros(p,N);
M_mat= zeros(p,N);
x_free_vec = zeros(1,N);
x_vec= zeros(1,N);

for n = 1 : N-1

U = sigma_u*randn(p,1);
H = A*H+U; % unknown channel update
V = [ v(n+1);v(n) ]; % known input
w = sigma*randn; % wgn
x_free = V'*H ; % Noiseless channel output
x = x_free + w; % Channel Output

h_hat_2 = A*h_hat_1;
M_2 = A*M_1*A'+Q;
K = ( M_2*V )./ ( sigma^2 + V'*M_2*V );
h_hat_1 = h_hat_2 + K*(x -V'*h_hat_2 );
M_1 = ( eye(p) - K*V' )*M_2;

%%% for plotting %%%
x_vec(n) = x;
x_free_vec(n) = x_free;

h_mat_True(:,n) = H;
h_mat_Est(:,n) = h_hat_2;

K_mat(:,n) = K;

M_mat(:,n) = [ M_1(1,1); M_1(2,2) ];

end

figure(1); %title('Realization of TDL coefficients');
subplot(2,1,1);
plot(h_mat_True(1,1:100), '--', 'LineWidth', 2);
hold on; grid on;
plot(h_mat_Est(1,1:100),'r', 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Tap weight, h_n[0]');
legend('True','Estimate');
ylim( [0 2] )

subplot(2,1,2);
plot(h_mat_True(2,1:100), '--', 'LineWidth', 2);
hold on; grid on;
plot(h_mat_Est(2,1:100), 'r', 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Tap weight, h_n[1]');
legend('True','Estimate');
ylim( [0 2] )


figure(2);
subplot(3,1,1);
plot(v(1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Channel input, v[n]');
ylim( [-1 2.5] )

subplot(3,1,2);
plot(x_free_vec(1,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
```

```
ylabel('Noiseless channel, y[n]');
ylim( [-1 2.5] )

subplot(3,1,3);
plot(x_vec(1,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Channel input, v[n]');
ylim( [-1 2.5] )

figure(3);
subplot(2,1,1);
plot(K_mat(1,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Kalman gain, K_1[n]');
ylim( [-.6 1.1] )

subplot(2,1,2);
plot(K_mat(2,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Kalman gain, K_2[n]');
ylim( [-.6 1.1] )

figure(4)
subplot(2,1,1);
plot(M_mat(1,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Min. MSE, M_11[n]');
ylim( [0 0.2] )

subplot(2,1,2);
plot(M_mat(2,1:100), 'LineWidth', 2);
xlabel('Sample number, n');
ylabel('Min. MSE, M_22[n]');
ylim( [0 0.2] )
```

[End of the Document]