4D Trajectories and Automation Connotations and Lessons Learned from Past Research

Embry-Riddle Aeronautical University

Center for Applied ATM Research

Overview

- ***Definitions***
- ***4D trajectories – some history***
- ***Trajectories for deconfliction***
- ***RNAV, Automation - Is anything new?***
- ***4DT Lessons Learned***
  - ***Prediction, Uncertainty, Accuracy***
  - ***Data Link, Definition, semantics, ontology***
  - ***Open and closed loop, 3D solutions for 4DT and CDA***
  - ***Ownership and Contracts***
  - ***UPTs, Complexity and self-organizing systems***
  - ***Defined track procedures***
- ***Simple 4DT ConOps and Transition***

New Technology New Possibilities!

New Enablers	***Availability***
aRea NAVigation to RNP 0.01	***New capability for NextGen***
Time Based Metering	***New Concept for NextGen***
Automated 4D Trajectory Based Control	***Available by 2015 in NextGen***
Tracking, Conformance Monitoring Automated 4DT update	***Available in NextGen***
Datalink negotiation of Trajectories	***NextGen requirement for trajectory based control***

New Technology New Possibilities!

New Enabler?	Availability
aRea NAVigation to RNP 0.01	Available in 1942 as Gee the Home Chain, became LORAN
Time Based Metering	New Concept for NextGen
Automated 4D Trajectory Based Control	Available by 2015 in NextGen
Tracking, Conformance Monitoring Automated 4DT update	Available in NextGen
Datalink negotiation of Trajectories	NextGen requirement for trajectory based control

New Technology New Possibilities!

New Enabler?	Availability
aRea NAVigation to RNP 0.01	Available in 1942 as Gee the Home Chain, became LORAN
Time Based Metering	Procedural and 4DT Control
Automated 4D Trajectory Based Control	Available by 2015 in NextGen
Tracking, Conformance Monitoring Automated 4DT update	Available in NextGen
Datalink negotiation of Trajectories	NextGen requirement for trajectory based control

New Technology New Possibilities!

New Enabler?	Availability
aRea NAVigation to RNP 0.01	Available in 1942 as Gee the Home Chain, became LORAN
Time Based Metering	Procedural and 4DT Control
Automated 4D Trajectory Based Control	Procedural Control automated in NAS Host software - late 60's
Tracking, Conformance Monitoring Automated 4DT update	Available in NextGen
Datalink negotiation of Trajectories	NextGen requirement for trajectory based control

New Technology New Possibilities!

New Enabler?	Availability
aRea NAVigation to RNP 0.01	Available in 1942 as Gee the Home Chain, became LORAN
Time Based Metering	Procedural and 4DT Control
Automated 4D Trajectory Based Control	Procedural Control automated in NAS Host software - late 60's
Tracking, Conformance Monitoring Automated 4DT update	Automated conformance monitoring in NAS Host in late 60's
Datalink negotiation of Trajectories	NextGen requirement for trajectory based control

New Technology New Possibilities!

OLD Capabilities	Available just not fully used
aRea NAVigation to RNP 0.01	Available in 1942 as Gee the Home Chain, became LORAN
Time Based Metering	Procedural and 4DT Control
Automated 4D Trajectory Based Control	Procedural Control automated in NAS Host software - late 60's
Tracking, Conformance Monitoring Automated 4DT update	Automated conformance monitoring in NAS Host in late 60's
Datalink negotiation of Trajectories	CPDLC since 1980's datalink trajectories (civil) mid-90's

Definitions 1

- ***<u>4D Trajectory</u>. The precise description of the flight path of an aircraft as a 4 dimensional continuum from its current position to the point at which it shuts down at its destination. (thus every point on a 4D Trajectory is precisely associated with a time)***
- ***<u>3D Trajectory</u>. The precise description of the flight path of an aircraft as a 3 dimensional continuum from its current position to the point at which it shuts down at its destination (There is no time associated with any point on a 3D trajectory)***

- ***Which of the above trajectories can be used for efficient deconfliction?***

Definitions 2

- ***3½ D Trajectory*. A 3D trajectory with Required Time of Arrival (RTA) defined for one or more points on the 3D continuum**
  - ***What is the difference between RTA and ETA? -***
- ***Optimal Trajectory*. A 4D trajectory which, if flown, would result in the most efficient use of the airline resources (as judged by the aircraft operator – a business decision)**
- ***User Preferred Trajectory (UPT)*. A UPT is a trajectory chosen by the aircraft operator; it is not necessarily optimal in any respect**

History and Procedural Control

- ***Aircraft flew from fix to fix marked by beacon fires, colored lights and then radio beacons***
- ***Eventually aircraft had to be separated in IMC***
- ***This is so called 'procedural control'***
  - ***Aircraft identifies fixes that it will cross (flight plans)***
  - ***Gives estimated time and level crossing each fix***
  - ***Controller copies this information onto paper strip for each fix with time and level***
  - ***If 2 strips at a fix have same time and level then delay one of the aircraft at preceding fix or alter its level***
  - ***Pass 'clearance' to the aircraft***
  - ***Monitor aircraft position reports at fixes***

History and Procedural Control

- ***Aircraft flew from fix to fix marked by beacon fires, colored lights and then radio beacons***
- ***Eventually aircraft had to be separated in IMC***
- ***This is so called 'procedural control'***
  - ***Aircraft identifies fixes that it will cross (3D Trajectory)***
  - ***Gives estimated time and level crossing each fix (4D UPT)***
  - ***Controller copies this information onto paper strip for each fix with time and level (Ground model of 4D Trajectory)***
  - ***If 2 strips at a fix have same time and level then delay one of the aircraft at preceding fix or alter its level (Conflict resolution)***
  - ***Pass 'clearance' to the aircraft (Trajectory Negotiation)***
  - ***Monitor aircraft position reports at fixes (Conformance Monitor)***
-

The ATM Safety Process

- ***Build model of aircraft trajectories***
- ***Monitor aircraft and correct model or aircraft trajectory if an aircraft deviates***
- ***Identify conflicting trajectories***
  - ***'What-if' model deconfliction***
  - ***Choose preferred deconfliction***
  - ***Transmit the deconfliction action to the aircraft***
  - ***Monitor the implementation of the deconfliction***
- ***Repeat***

- ***This can be a cognitive or an automated process and is the same for radar and procedural control***
- ***Note that 4D trajectories are used even if only in the controllers head***

Trajectory Based Operations

- ***Trajectory based operations are not 'new'***
- ***What is new:***
  - ***Accuracy of the aircraft implementation of trajectory (ANP)***
  - ***Accuracy of passing information with Communications via data link (RCP)***
  - ***Surveillance capabilities dependent and non-cooperative***
  - ***Automation and Decision Support Tool capabilities***
- ***Vast improvements in accuracy speed and capabilities***

Trajectory 'Prediction'

- ***Trajectory 'prediction' is or should be a misnomer***
- ***If an aircraft is cleared to fly a certain trajectory, even in today's system, they will fly it within the bounds of the accuracy of the clearance***
  - ***Fly* WEST *from KORD to KIAD is very inefficient but as the aircraft flies that trajectory it can be safely deconflicted***
- ***Guidance from the FMS or the Ground provides feedback to keep an aircraft on trajectory***
- ***Cannot be called a 'prediction' unless there is no tracking and/or no feedback loop***
- ***Trajectory Generation is a more correct term***
- ***Accurate generation of a 4D trajectory is efficient***
- ***Accurate Navigation on a 4D trajectory is safe as the 4DT is used for deconfliction***

RNAV – RNP

- ***aRea NAVigation – RNAV – the capability to navigate anywhere without the need to overfly radio beacons***
- ***This is NOT new, aircraft have had this capability for nearly 65 years***
- ***Can use VOR/DME, TACAN, GPS, LORAN etc***
- ***Specifications now require specific aids and alarm levels set based on the RNP***
- ***Required Navigational Perforrmance – RNP – specified in miles or decimal fractions of a nautical mile***
- ***RNP 1 means fly to an accuracy of 1 nautical mile, RNP 0.001 means fly to the accuracy of 1/1000 of a nautical mile (around 6 meters)***

Accuracy

- ***Accuracy is ANP NOT the same as Required Navigational Performance (RNP)***
- ***The FMS generates a trajectory and then controls the aircraft along the trajectory as accurately as possible***
- ***Modern levels of en-route FMS accuracy can be measured within 10 meters or less with no altitude error and within 10 seconds***
- ***The alarm levels on the FMS / navigation systems may be set far wider than the achieved accuracy***
- ***RNP requires that an aircraft fly within the RNP parameter for 95% and not more than twice the parameter from the trajectory at any time***
- ***Leads to the concept of an RNP 'bubble' width RNP parameter and length of around 10 secs***
- ***Aircraft can fly smoothly within bubble***

Language Data link and Trajectories

- ***Assume an aircraft FMS has generated an RNP 0.001 trajectory with a variable descent starting in a series of 'S' turns***
- ***This cannot be described by radio or CPDLC as both use 'natural language'***
- ***Thus aircraft without data link or even with CPDLC have the accuracy of their handling limited by the limitations of the communication medium to describe the trajectory***
- ***Aircraft with no datalink still have a trajectory but it will be stylized by its description in words***
- ***Alternatively the ground system may display the trajectory and advisories to a controller who then passes instructions to fly the aircraft along the trajectory***
- ***Aircraft <u>with</u> datalink can pass precise data between systems and have no trajectory limitations***
- ***Allows communications with graphical representations of trajectory***
- ***Datalink is therefore an enabler for precise 4D Trajectory Based control systems***

Standard Trajectory Definition?

- ***The presentations here are all about trajectories***
- ***Trajectories are fundamental to safe Air Traffic Management.***
- ***Trajectories are being used in:***
  - ***Airborne Separation Assurance, TCAS, ADS-B, several Ground systems and their differing tools NAS, URET, CTAS, MTCD, CORA etc***
- ***Air FMSs are using ARINC 702a/429/664 effectively arrays of points rather than an object oriented approach to describe a continuum***
- ***In the PHARE programme the data part of the trajectory object was exchanged – subsequent exchanges sent only the changes in the data part***
- ***This approach led to a huge reduction in data transmissions and increase in accuracy***

Trajectory Definition [2]

- ***All tools and systems that use trajectories should have:***
  - ***Precisely the same data definition, semantics, and ontology.***
  - ***No misunderstanding of the information content***
- ***Ontology – the capability to assume the other person knows what you mean***
  - ***What is a YF-12A ? So what is a YF-12D ?***
  - ***More importantly - What is 'altitude' ?***
- ***If different trajectories are used with different syntax and semantics based on differing ontologies - it will be DANGEROUS***

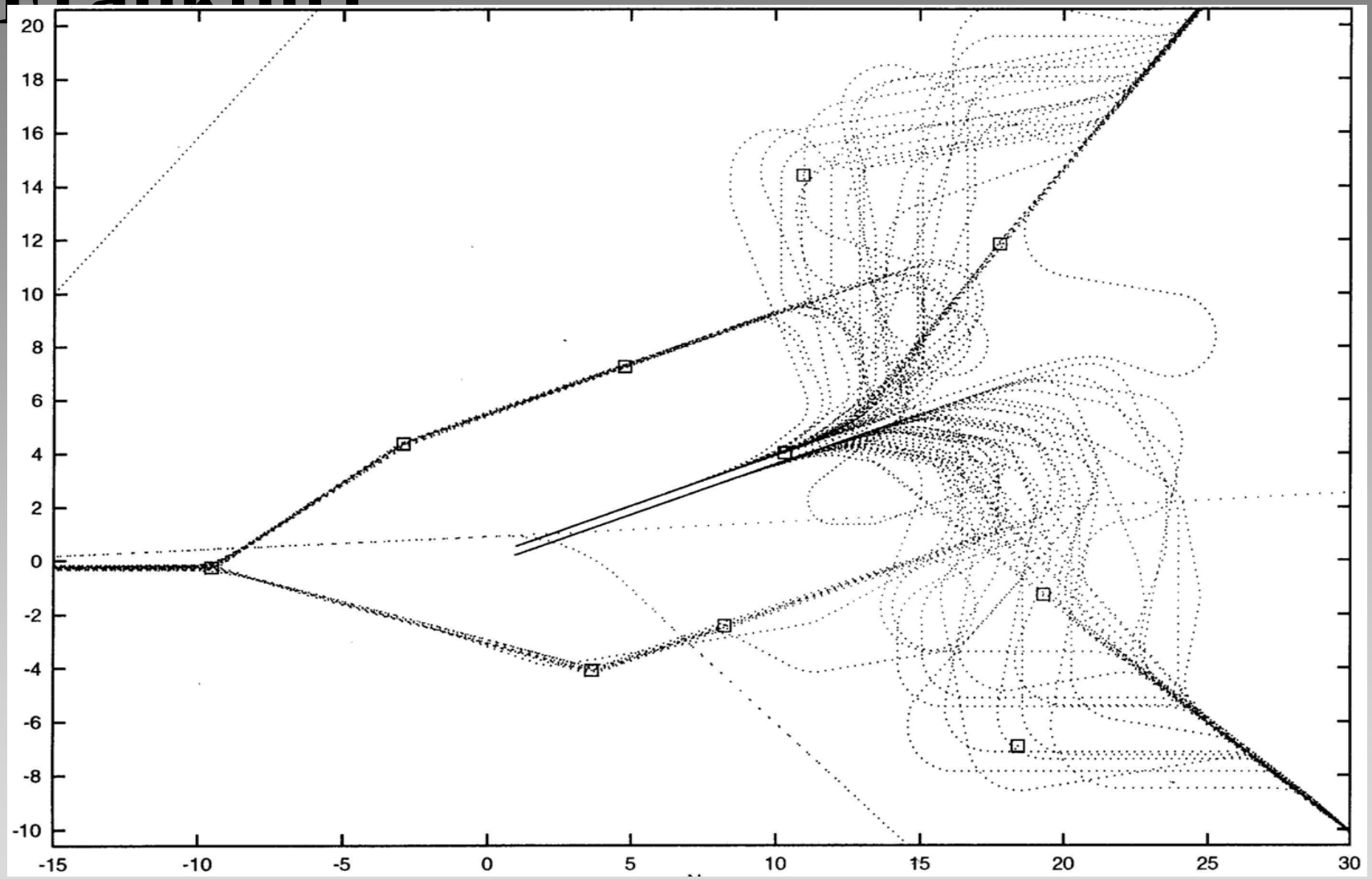
Ground Tracks

- ***FMS/RNAV procedures are based on ground tracks and ground radius variable bank turns***
- ***FMS's only have maximum 22° bank control authority (some airlines less)***
- ***Generic procedures based on ground radius turns will be inefficient or unflyable for some aircraft***
- ***Wind is not a problem for the controller as the aircraft trajectory guidance follows a track***
- ***Wind forecasts are accurate to 5kts ground speed***
- ***Airspeed corrections at height mean that 5Kts is 2.5Kts IAS easy to correct an error of this magnitude***

Closed Loop Trajectories

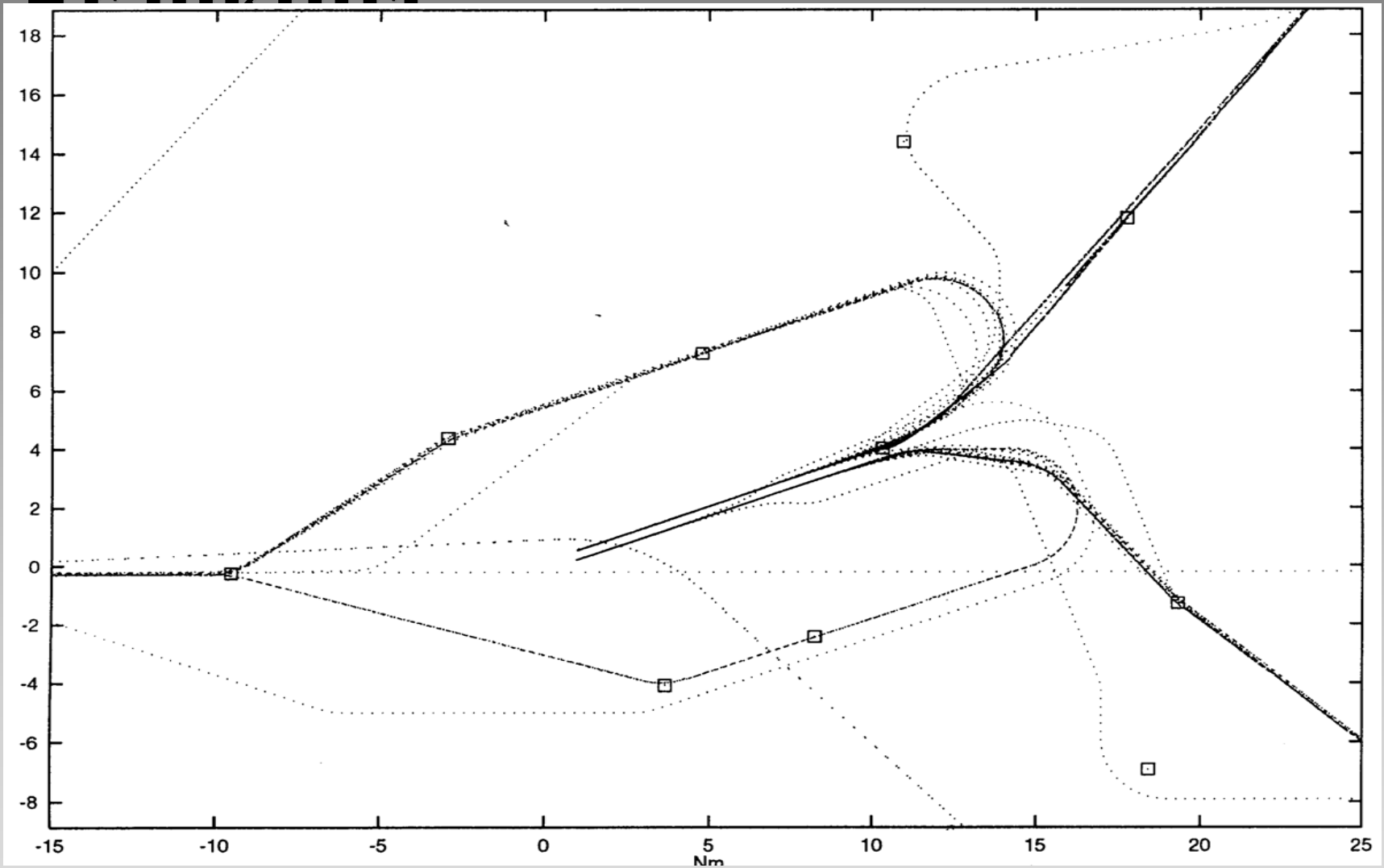
- ***Fill in the blank: "Turn left <blank> 300"***
- ***What is wrong in using 'heading'?***
  - ***Giving a heading is open ended and potentially as dangerous as just saying "descend" without a bottom limit***
  - ***A 4D trajectory turn will be on a TRACK not a heading and is following the trajectory***
- ***What is wrong with using turn left track 300?***
- ***Breaks in the trajectory continuum MUST be avoided:***
  - ***They prevent tools like conflict probes and conformance monitors working***
  - ***They increase the risk of conflicts and CFIT***
  - ***They reduce the accuracy of arrival sequencing and the efficiency of the flight***
- ***A 4D Trajectory is gate to gate and is a continuum - breaks in these trajectories are dangerous***

‘Conventional’ Radar Control - Frankfurt



PHARE PD/2 1996

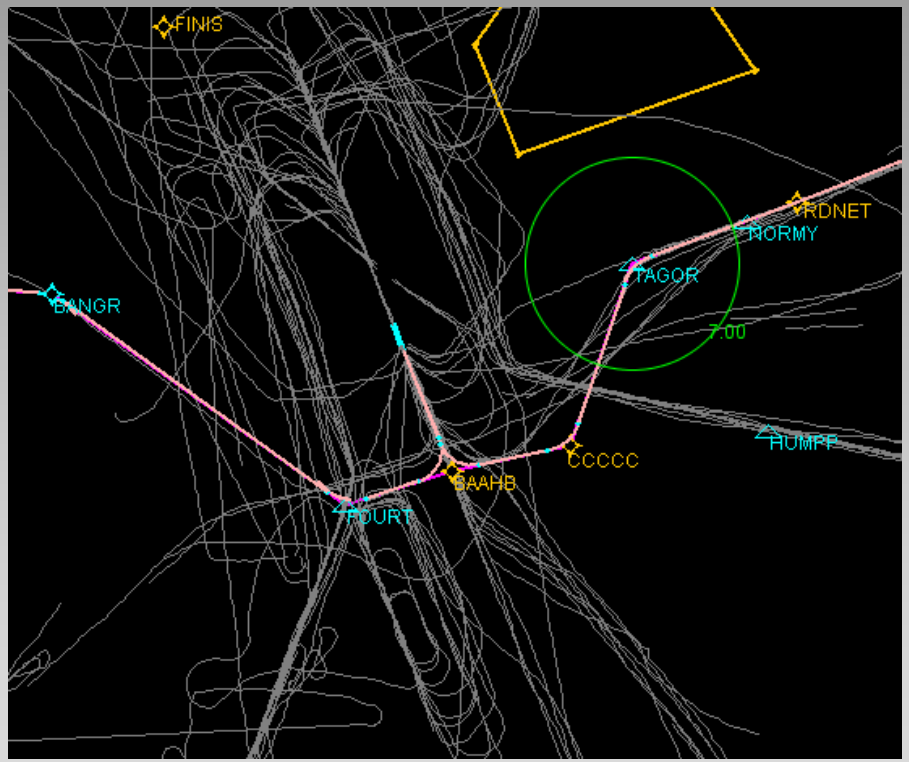
RNAV-RNP with Datalink - Frankfurt



PHARE PD/2 1996

FAA RNAV/RNP Approaches

- ***Currently, RNAV procedures are based on historic 3D tracks***
- ***Uploaded to the FMS and flown by aircraft***
- ***TARGETS uses this methodology***



Single Lane for next 100 miles

- ***'RNAV should not be used as a way of forcing aircraft to accurately follow a line, but as a way of accurately knowing where an aircraft will be' (CEO Jet Blue)***
- ***Current FAA usage of RNAV-RNP is to force aircraft to follow a single precise trajectory***
- ***Inefficient for the aircraft puts B777 behind ATR42***
- ***This problem shown in EUROCONTROL research in 1996 now being replicated by FAA a decade later***
- ***Prevents efficient Continuous Descent Approaches***

Continuous Descent Approaches (CDA)

- ***CDA can reduce:***
  - ***fuel usage/emissions***
  - ***Noise and noise footprint of airport***
  - ***Reduce flying time and cut operating costs***
- ***Problem:***
  - ***aircraft have differing ideal descent rates and speeds***
  - ***Use of fixed precise RNAV/RNP STARs requires extra separation***
  - ***Runway utilization can drop by 50%***
  - ***Use of fixed STARs with sophisticated tools and restricting the aircraft the runway utilization reduction limited to a few percent***
- ***Unfortunately NextGen requires an increase in runway utilization***

CDA and Runway Efficiency

- ***If CDA are flown on diverse UPT to a touchdown time***
  - ***All the benefits of CDA are available***
  - ***The aircraft fly their own preferred speeds and descent rates***
  - ***Runway utilization can be maintained or increased***
  - ***What noise there is spread***
  - ***Requires DST to sequence and deconflict***
  - ***These DST have been available for 10 years***
- ***Should not forget climb phase***
  - ***Single power setting climb very efficient***
  - ***Steady climb rate separates inbound and outbound traffic***

Contracted Trajectory

- ***Negotiation of trajectory results in a 'contract' between the aircraft and 'the system'***
- ***Contract:***
  - ***Aircraft shall follow the contracted trajectory (broadcast intent) unless a new trajectory is negotiated – in emergency the negotiation can be pre-empted***
  - ***The System shall ensure that the contracted trajectory is kept conflict free – or negotiate a new trajectory***
- ***This contractual approach results in airspace in which all trajectories are known and can be relied on for deconfliction***
- ***EUROCONTROL research showed renegotiation of a trajectory over data link using graphical inputs for pilot and controller typically took less than 30 seconds***

Large Sectors – Long Look Ahead

- ***The use of the 4D tools is suited to larger sectors and allows a longer planning horizon.***
- ***Long planning horizon also allows longer MTTR in failure cases***
- ***Gate-to-gate 4DT allow controllers to solve trajectories downstream of their sector***
- ***Teamwork across boundaries increases capacity and decreases workload***
- ***The 'system' should not enforce rules for planning inside or outside sectors.***
- ***Why delay of conflict resolution until 'just-in-time' when resolution can be done safely 300NM away with 4DT DST?***

Self Organization and Flows

- ***UPTs will tend to be simple long legs – there will not be complex patterns***
- ***Simulations showed complex sectors becoming simple***
- ***Current system is 'file and forget' planning followed by request for clearance - requires flow management***
- ***4DT / TBO can be more interactive trajectories causing overload can be rejected to the operator***
- ***Leads to a self-organizing system with distributed flow management decision making***
- ***Flow management will need to change as Miles-In-Trail and metering fixes will not be valid***

Disruptive 3D Techniques in 4D System

- ***Separation***
  - ***using ASAS or ground DST uses an RNAV/RNP based 4D Trajectory***
  - ***If the pilot takes control 'to avoid weather'***
    - ***FMS can no longer broadcast an intent***
    - ***all deconfliction and sequencing is unsafe***
- ***Station Keeping, In-Trail***
  - ***The aircraft can either fly its contracted 4DT or station keep, it cannot do both***
  - ***If the aircraft starts station keeping***
    - ***FMS can no longer broadcast an intent***
    - ***all deconfliction and sequencing is unsafe***

Proposed 4DT ConOps

- ***Aircraft define 4D UPT within their capability and transmit to the ground***
- ***If not equipped or no datalink, the ground system defines 4DT for them***
- ***Ground DST deconflict 4DT and sequence***
- ***Air and ground contract the 4DT***
- ***ASAS/TCAS and ground DST monitor 4DTs***
- ***Departures taxi out on trajectory and take off for single power setting climb en-route***
- ***Arrivals Diverse UPT CDA to touchdown then 4DT to gate***
- ***Minimum of airspace restrictions***
- ***Unmanaged airspace no change***

Transition Case

- ***The transition case will last decades***
  - ***Aircraft being delivered now not equipped***
  - ***Life of existing and new aircraft 20 years or more***
- ***All aircraft have a 4D trajectory – some cannot define or transmit it accurately***
- ***ANSP should put 4D DST in place – this is possible with ERAM and ATOP***
- ***ANSP then uses 4D DST to control aircraft using 4D Trajectories***
- ***Unequipped aircraft get less efficient 'pixelated' trajectories***
- ***When aircraft are equipped, they can immediately fly UPT on more efficient routes – rewarding the investment***
- ***There is no need for mandates***

Low Hanging Fruit

- ***Oceanic airspace could be converted to 4D UPT very rapidly***
- ***Use space based ADS-B or HF ADS***
- ***Use space based voice comms (VOIP) or HF***
- ***Trajectory based separation on cruise climb UPT (reduces conflict risk considerably)***
- ***Slightly extended radar separation say 30 miles***
- ***TCAS / ASAS as backup***
- ***Potential savings are huge – tons of fuel per flight***

Thoughts to ponder...

Aircraft can be given‘user preferred trajectories’ including:

unrestricted climbs -- cruise climb -- flight idle descents

the effects are:

Significant fuel savings and/or payload increases

Significant reduction in conflicts

Reduced airspace congestion

Reduced delays

Reduced air pollution

Reduced noise pollution

Why don’t we do it ?

Thoughts to ponder...

Aircraft can be given‘user preferred trajectories’ including:

unrestricted climbs -- cruise climb -- flight idle descents

the effects are:

Significant fuel savings and/or payload increases

Significant reduction in conflicts

Reduced airspace congestion

Reduced delays

Reduced air pollution

Reduced noise pollution

Why don’t we do it ?

Slide first presented - March 1997