

Supporting
European
Aviation



Mode S Surveillance Principle

MICA Workshop for ICAO MID States
Agenda Item #1

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EUROCONTROL MICA Cell

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Content

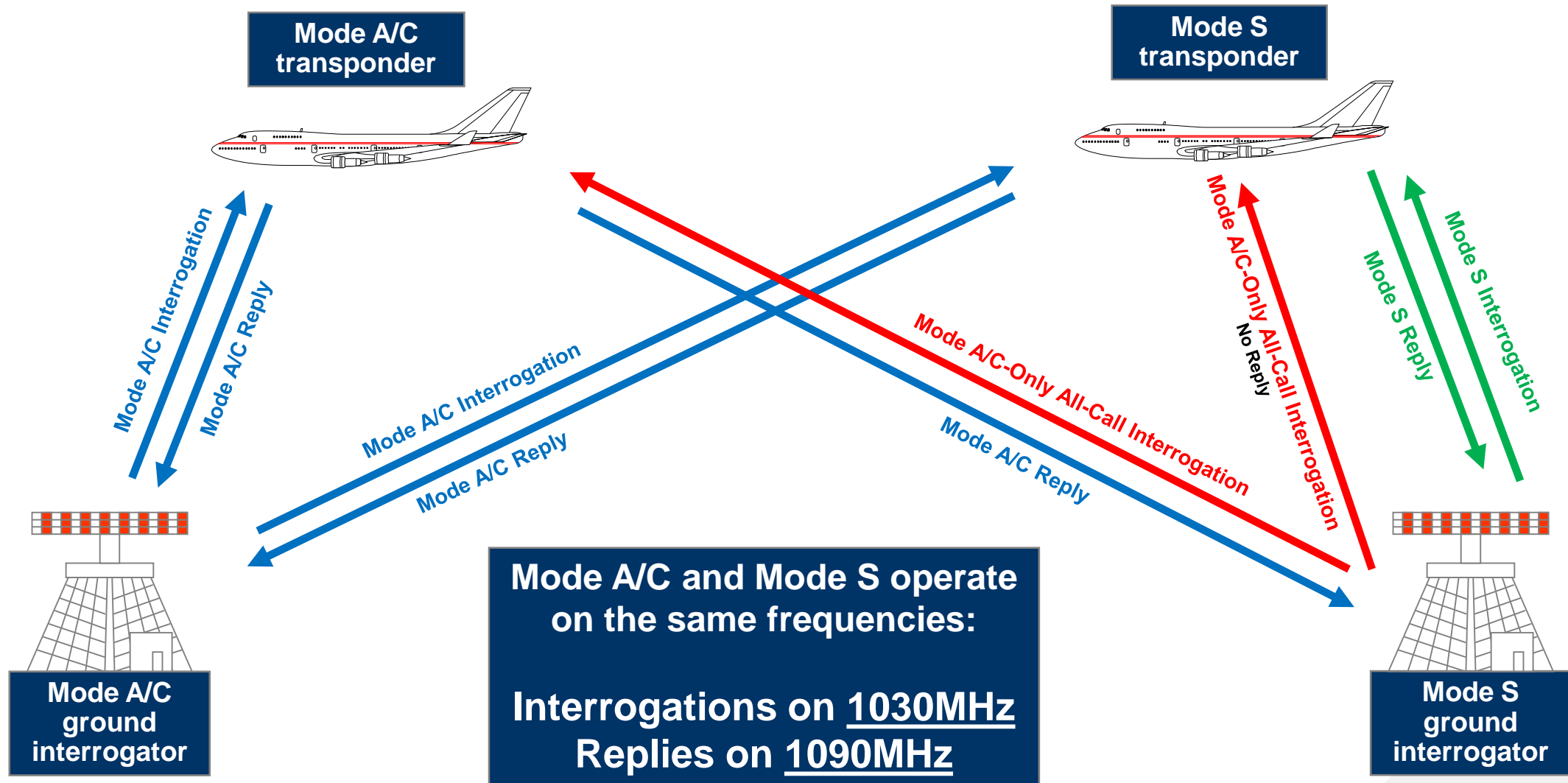
- Description of the key technical principles of Mode S radar
 - Interrogator Code (IC)
 - more details in “Operation on II and SI Code, II/SI Code Operation”
 - Coverage Maps
 - Lockout
 - Clusters
- Description of Mode S radar operation, interrogations and replies
- Overview of other surveillance systems:
 - ADS-B
 - Multilateration (WAM)
 - Airborne Collision Avoidance System (ACAS)

- **S = Selective**

- Selectively communicate with **individual** aircraft

- Unique Mode S address for each aircraft (ICAO 24-bit aircraft address)
 - Allocated by the State at registration
- An 'address' for Mode S radar (IC = Interrogator Code)
 - Provided by the EUROCONTROL MICA (Mode S Interrogator Code Allocation) Cell
- Backward compatible with old systems (Mode A/C)

Mode S and Mode A/C - Interrogations and Replies



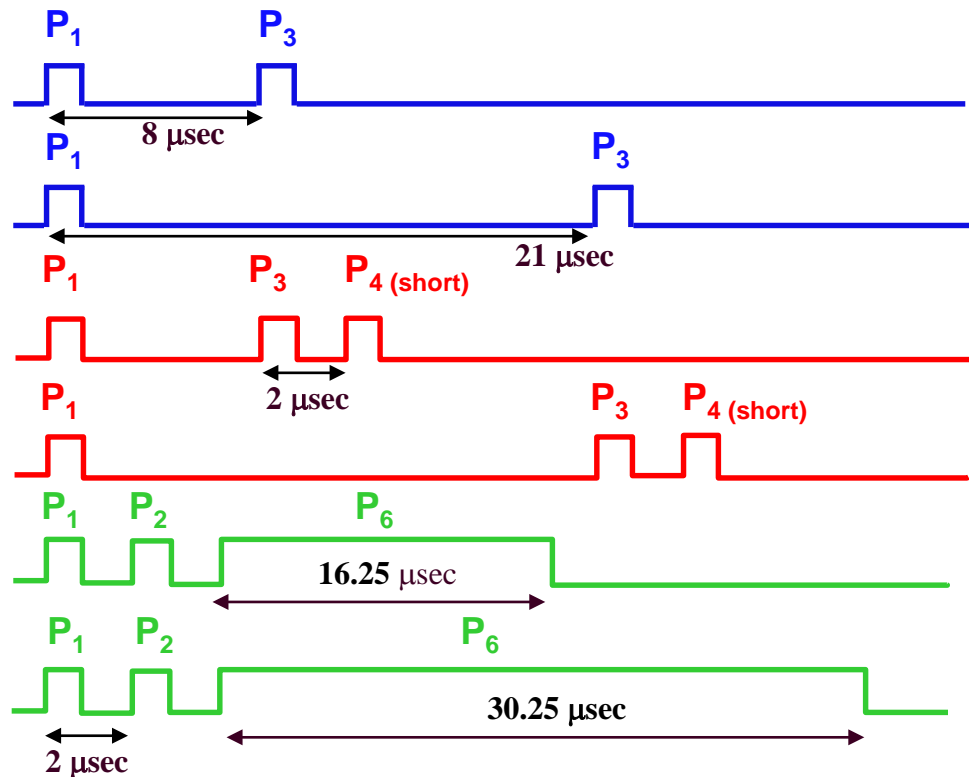
Mode S and Mode A/C interoperability

MODE A/C

**Mode A/C-Only
all-call
(Intermode)**

MODE S

Interrogation Pulse Sequences (1030 MHz)



Name

MODE A

MODE C

MODE A-Only
all-call

MODE C-Only
all-call

MODE S Short

MODE S Long

Mode-A/C transponder	Mode-S transponder
MODE A	MODE A
MODE C	MODE C
MODE A	No Reply
MODE C	No Reply
No Reply	Mode S (All-Call or Roll-Call if selective)

**Transponder Replies
(1090 MHz)**

Mode A/C/S all-call interrogations (P₁ P₃ P₄ (long)) shall not be used on or after 1 January 2020 (See Section 3.1.2.1.5.1.1.1 of ICAO Annex 10 Vol. IV Fifth Edition)

Mode S Radar Interrogations

1. ACQUISITION → All-Call

A Mode S radar sends All-Call interrogations to detect and acquire incoming aircraft:

- Broadcast interrogations → addressed to all aircraft
- Aircraft reply with its ICAO 24-bit Mode S address

2. SELECTIVE INTERROGATIONS → Roll-Call

Once acquired, the Mode S radar sends selective interrogations to the aircraft using the 24bit Mode S address received during the acquisition

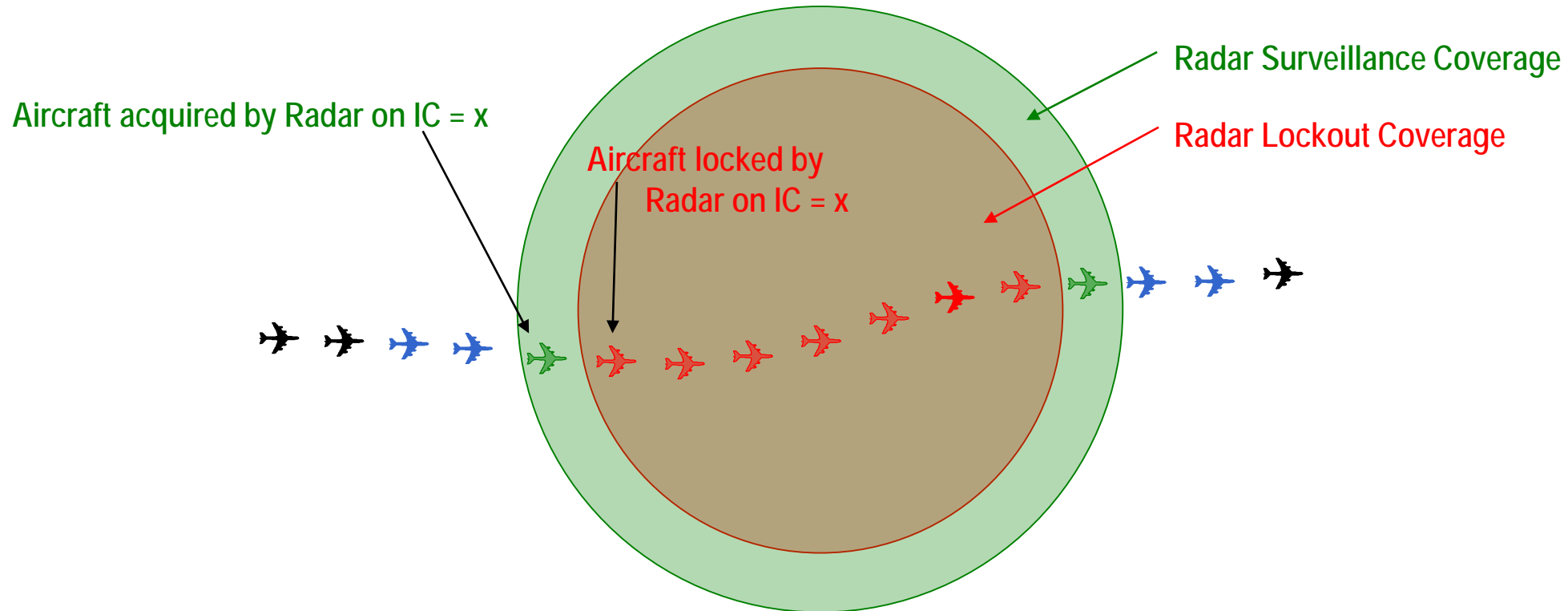
→ Selective interrogations in Surveillance coverage

3. LOCKOUT

Once acquired, the Mode S radar locks the aircraft to prevent it to reply to All-Call interrogations (lockout request in selective interrogations)

- All-Call replies are useless once the radar has acquired the aircraft.
- Lockout in Lockout coverage

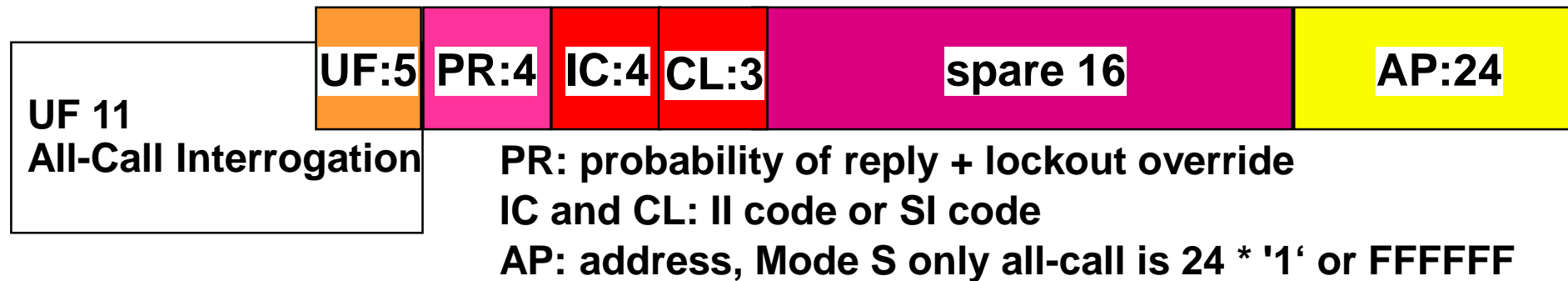
Aircraft acquisition, selective interrogations and lock-out



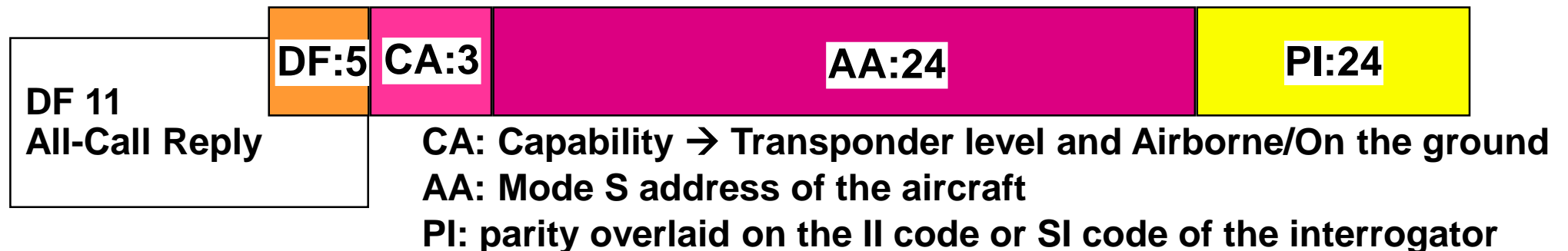
- ✈ Aircraft not in line of sight of radar and/or not in power budget → does not receive All-Call interrogations
- ✈ Aircraft outside surveillance coverage → receives All-Call interrogations and replies, but replies not processed by radar
- ✈ Aircraft acquired by radar in surveillance coverage using All-Call replies → selective interrogations (Roll-Call)
→ not locked: receive All-Call interrogations and replies
- ✈ Aircraft locked by radar in lockout coverage → does not reply to All-Call interrogations

All-Call Interrogation and Reply Format

Mode S Only All-Call Interrogation (UF 11) – 56 bits



Mode S Only All-Call Reply (DF 11) – Short: 56 bits



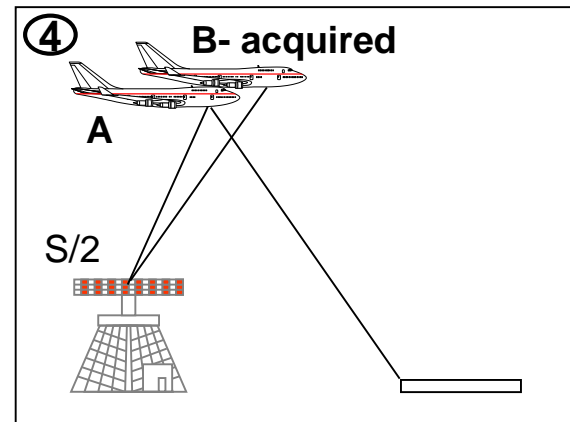
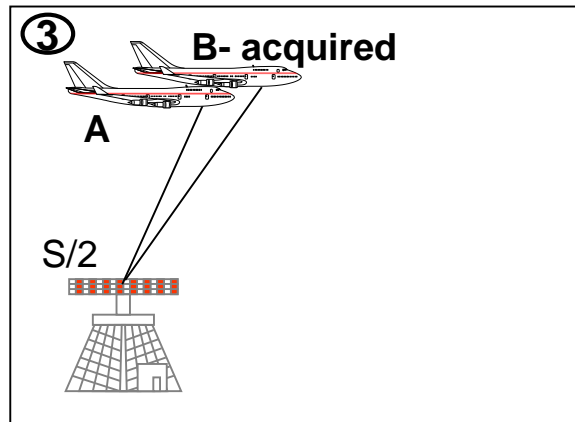
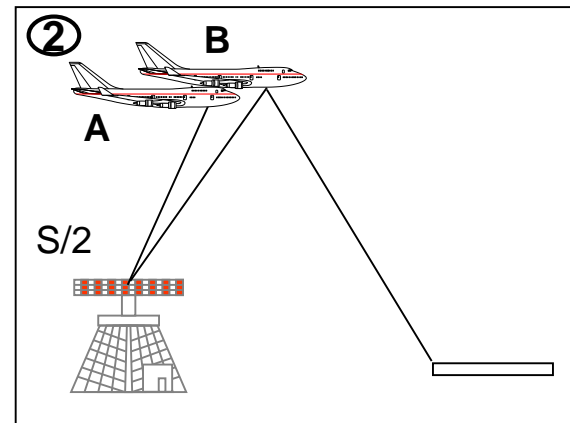
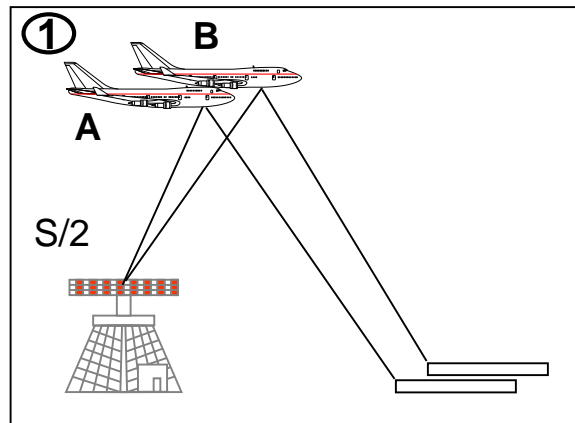
Aircraft Acquisition using All-Call

1. Mode S radar sends All-Call interrogations (UF11) to all aircraft (broadcast).
 - UF11 contains the IC (II or SI code) allocated to the Mode S radar
2. Mode S aircraft receives the All-Call interrogation (UF 11) and decodes the IC.
 - If it is not locked on this IC (or if lockout override is requested), the aircraft replies to the All-Call interrogation (All-Call reply – DF11) with the requested probability.
 - IC of Mode S radar and ICAO 24-bit Mode S address of the aircraft are in the All-Call replies.
3. Mode S radar receives All-Call reply (DF 11) containing its own allocated IC
 - Decodes the ICAO 24-bit Mode S address of the aircraft
 - Computes the aircraft position (range, azimuth)
 - If the aircraft is inside the Surveillance coverage, it is acquired and interrogated selectively

Stochastic Acquisition and Lockout Override

- Stochastic Acquisition
 - Probability of reply in All-Call interrogation
 - Used for acquiring targets close in range
- Lockout Override
 - Disregard aircraft lockout on IC in All-Call interrogation
 - Can be stochastic
 - Can be applied by sector
 - Sectorised lockout override by azimuth sector
 - Should not be used except for fall-back (e.g. in case of IC conflict) or temporary IC allocation

Stochastic Acquisition



Stochastic S/2 Interrogations with 50% set as PR

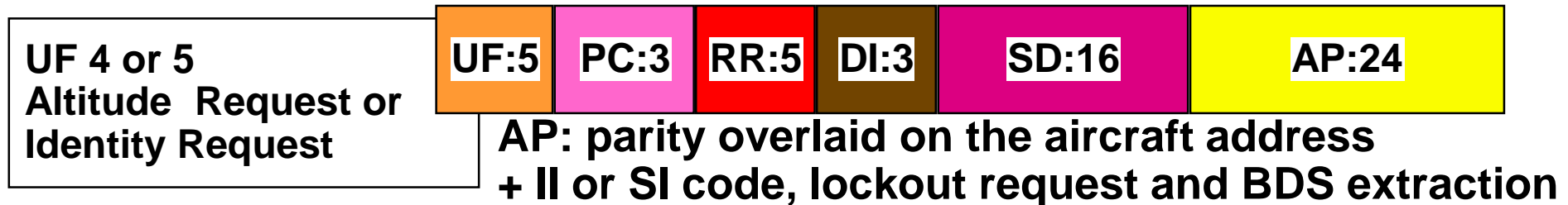
- ① A and B both reply
Replies overlap in time
Both are garbled and lost
- ② A decides No Reply (50%)
B replies
B acquired and locked out
- ③ B is locked out
A decides No Reply (50%)
- ④ B is locked out
A replies
A acquired and locked out

Selective Interrogations and Lockout

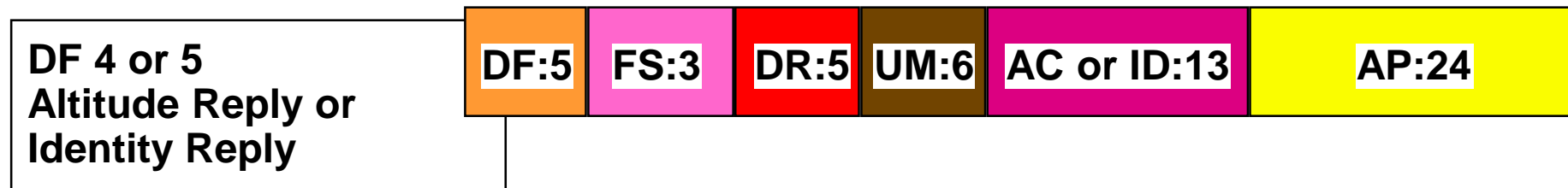
- Once an Mode S aircraft is acquired, the Mode S radar knows:
 - ICAO 24-bit Mode S address of the aircraft
 - Position of the aircraft
- ➔ Mode S radar sends selective interrogations to the aircraft using the ICAO 24-bit Mode S address in the Surveillance coverage (UF 4 or UF 5):
 - Only the aircraft having the correct ICAO 24-bit Mode S address replies
 - Request Altitude (Mode C) (UF 4) or Mode A Code (UF 5)
 - Lockout request in Lockout coverage to prevent the aircraft to reply to All-Call interrogations from the same radar (on the IC of the radar)
 - All-Call replies are useless once the radar has acquired the aircraft.
 - The Mode S radars with a fixed position should use permanent lockout.
 - May request the transfer of aircraft registers
 - BDS (Comm-B Data Selector)

Selective Interrogation and Reply Format

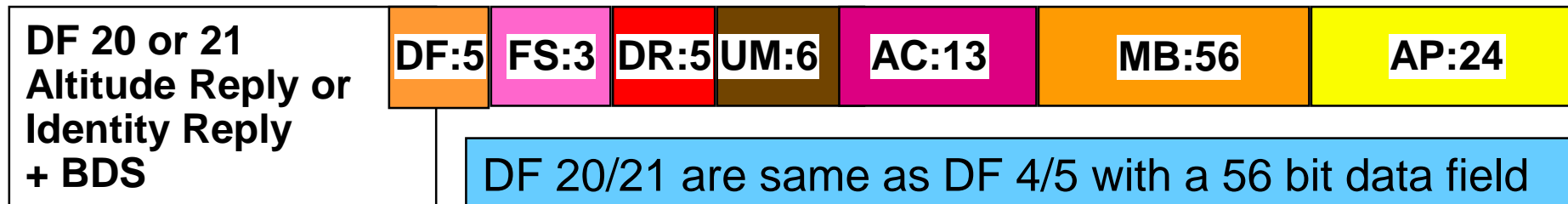
Surveillance Interrogation (UF 4 or 5) - 56 bits



Surveillance Reply (DF 4 or 5) – Short: 56 Bits (no BDS extraction)



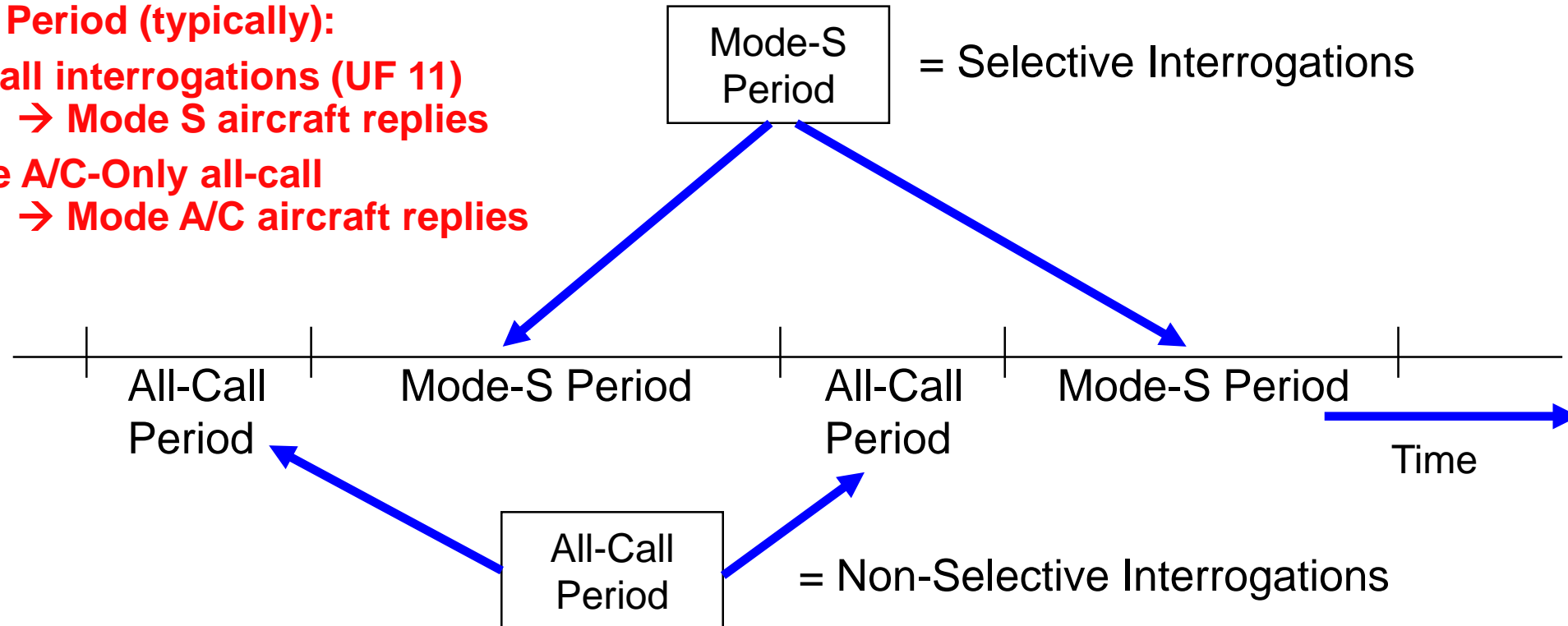
Comm-B Reply (DF 20 or 21) – Long: 112 Bits (content of BDS – MB:56)



All-Call Period vs. Mode-S Period (1)

All-Call Period (typically):

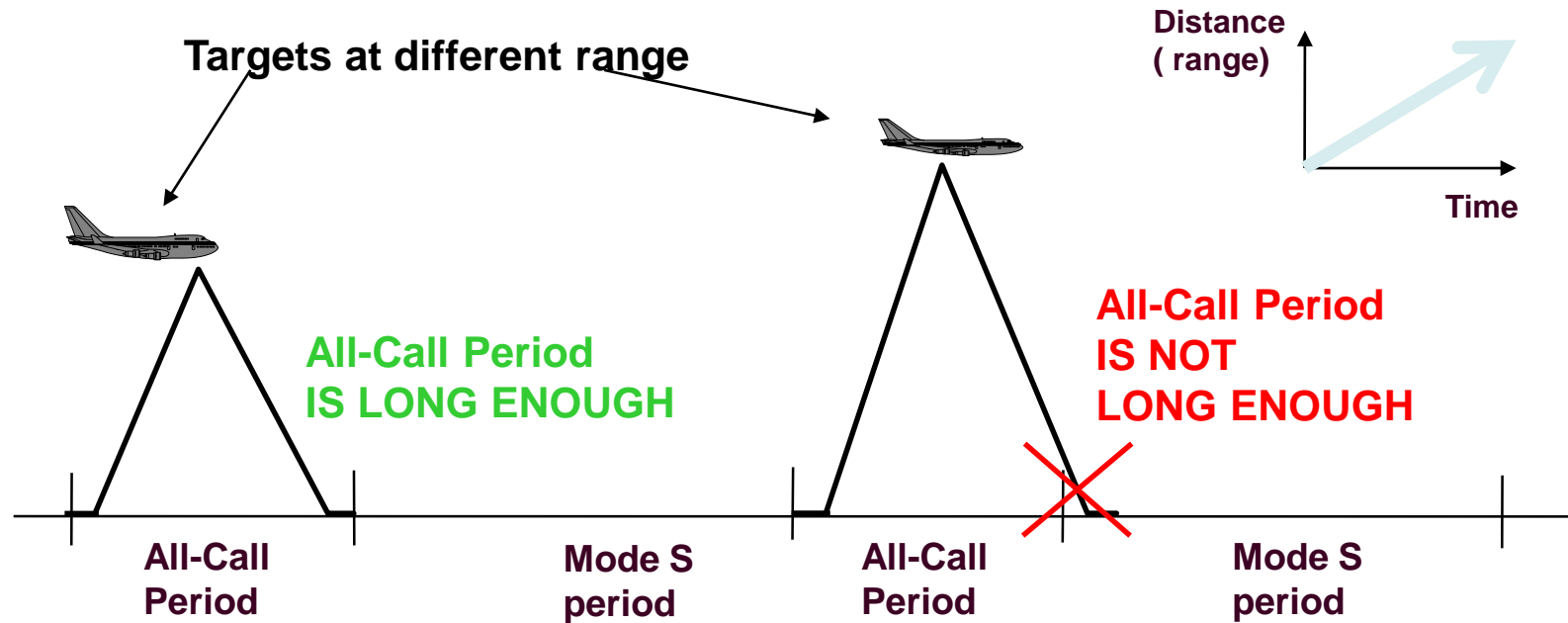
- All-Call interrogations (UF 11)
→ Mode S aircraft replies
- Mode A/C-Only all-call
→ Mode A/C aircraft replies



The Mode-S Period is also known as the Roll-Call Period

The mode interlace pattern (MIP) of an interrogator is the sequence of Interrogation periods (All-Call and Roll-Call Periods) that an interrogator is repeating.

All-Call Period vs. Mode S Period (2)



The length of the All-Call period must be AT LEAST long enough to allow an All-Call interrogation and reply sequence to complete (radar range).

Mode S All-Call and Mode A/C (-Only all-calls) interrogations can be sent in the same All-Call period or in different All-Call periods.

Requirements and Recommendations

- Mode S radar shall trigger, in average, less than 6 All-Call replies in the beam per aircraft
→ ICAO Annex 10 Vol. IV

3.1.2.11.1.1.2 Maximum number of Mode S all-call replies triggered by an interrogator. For aircraft that are not locked out, a Mode S interrogator shall not trigger, on average, more than 6 all-call replies per period of 200 ms and no more than 26 all-call replies counted over a period of 18 seconds.

- Mixed Mode MIP (i.e. MIP including Mode A/C interrogations – no short P4) should not be used.
- Mode S all call MIP should contain some interrogations with PR=1/2 or lower to facilitate the acquisition of aircraft in garbling situation and to reduce the number of triggered all call replies.

Elementary Surveillance (ELS)

- Basic Surveillance functionality
 - ICAO 24-bit technical identification
 - Mode A code and Mode C (Altitude reporting to 25ft)
 - Transponder capability reports
 - Datalink capability report (BDS 1,0)
 - Common usage GICB report (BDS 1,7)
 - Aircraft Identification - call sign (BDS 2,0)
 - Flight status (airborne / on the ground)
 - SI-Code functionality
- The provision of registers BDS 1,0, BDS 1,7 and BDS 2,0 is mandated for all aircraft
- These registers are requested in the first selective interrogations
- The content of these registers should not change under normal flight conditions
 - If it does, it should be broadcasted

Enhanced Surveillance (EHS)

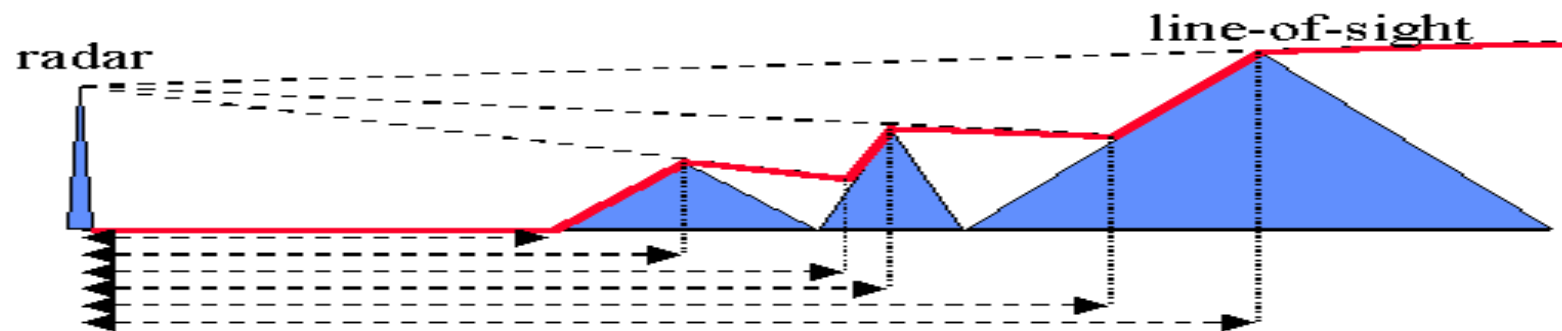
- EHS register availability known from BDS 1,7
- 3 BDS registers are in general regularly extracted.
- BDS 4,0 - Selected Vertical Intention
 - Selected Altitude / Barometric Pressure Settings
- BDS 5,0 – Track and Turn
 - Roll Angle / True Track Angle / Ground Speed / Track Angle Rate / True Airspeed
- BDS 6,0 - Heading and Speed
 - Magnetic Heading / Indicated Airspeed / Mach / Barometric Altitude Rate / Inertial Vertical Rate

Mode S Radar Coverage

- 3 formats of to define surveillance and lockout coverage
 - European Mode S (EMS) Coverage Map
 - Maps in Latitude/Longitude with same common origin (Latitude 33° North and Longitude 15° West) and same cell size (Δ Latitude: 0.0833° and Δ Longitude: 0.1253°)
 - EMS Coverage maps allocated by the MICA Cell when supported by Mode S radar
 - Lockout coverage is 1 cell smaller than the Surveillance coverage in IC allocations
 - Surveillance and Lockout range per sector
 - Surveillance and Lockout coverage divided into sectors (e.g. 32 sectors of 11.25°)
 - Surveillance and Lockout ranges provided by sector
 - Lockout range is 5NM smaller than the Surveillance range in IC allocations
 - Surveillance and Lockout unique range (circular coverage)
 - One unique surveillance range and one unique lockout range (circular coverage)
 - Not flexible for IC allocation

Line of Sight

- Radar coverage is limited by **Line of Sight**
 - Cone of Silence (or 'Overhead Gap')
 - Min & Max Elevations (e.g. 0 to 60 degrees)
 - Depends on antenna design and configuration
 - Obstacles

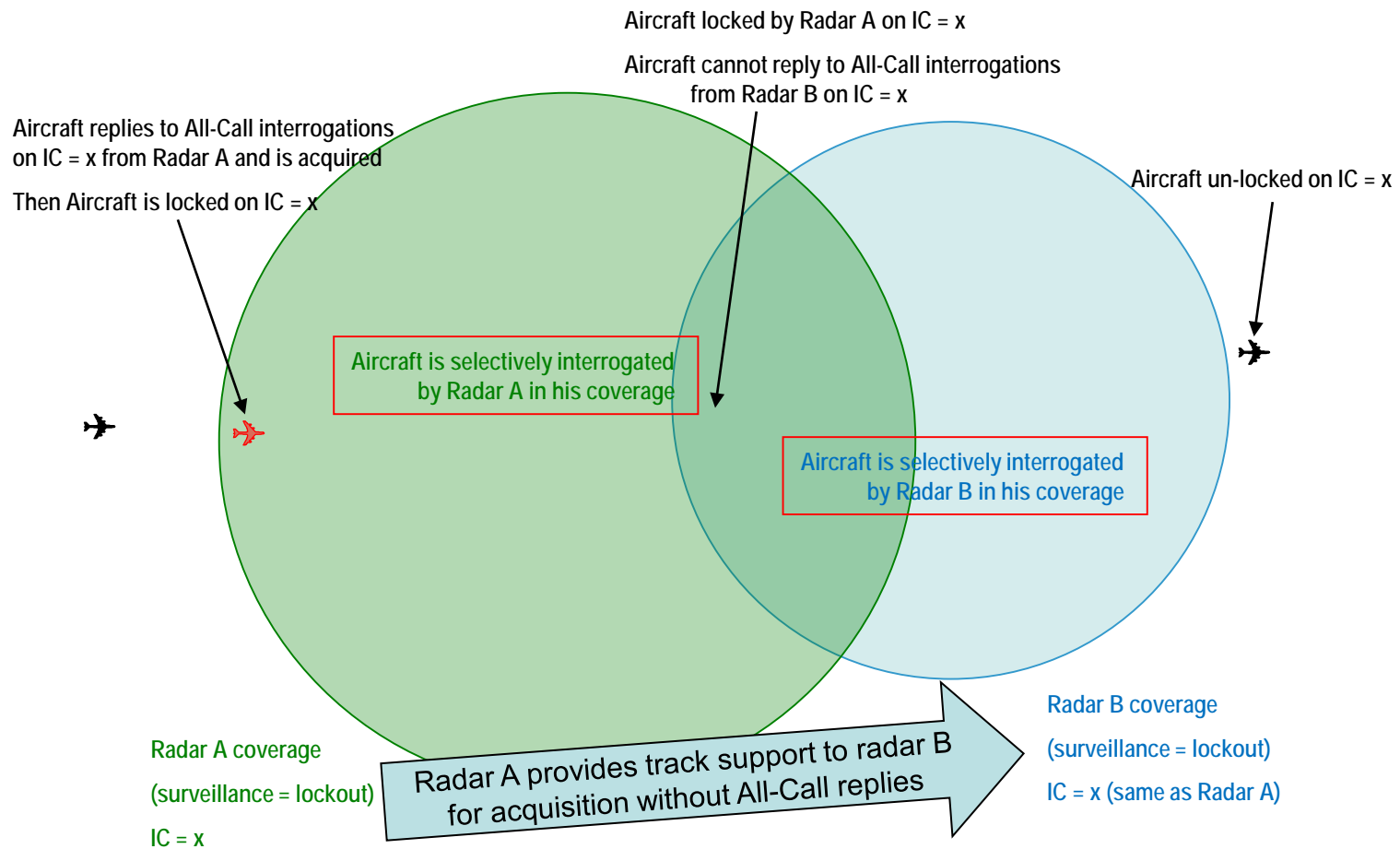


Cluster – operating stations together

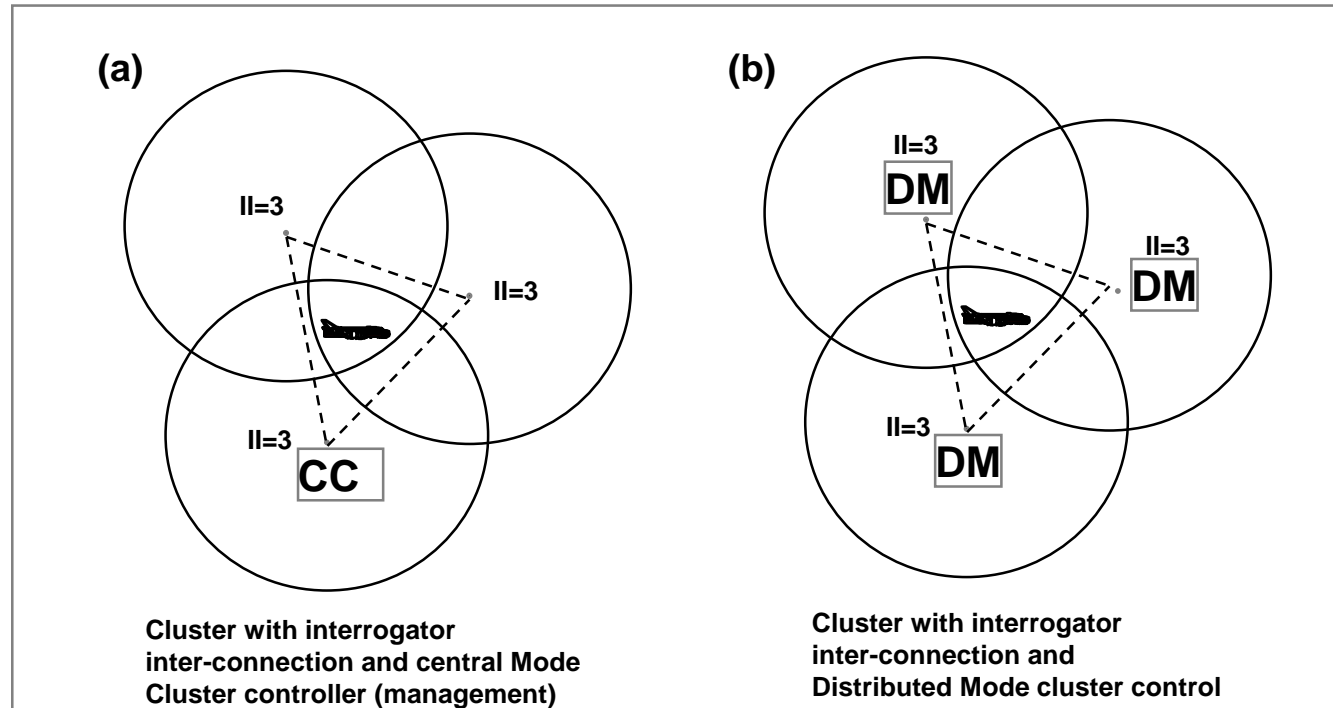


If an aircraft is in the cover of several radars, then they could share that information via ground data links.

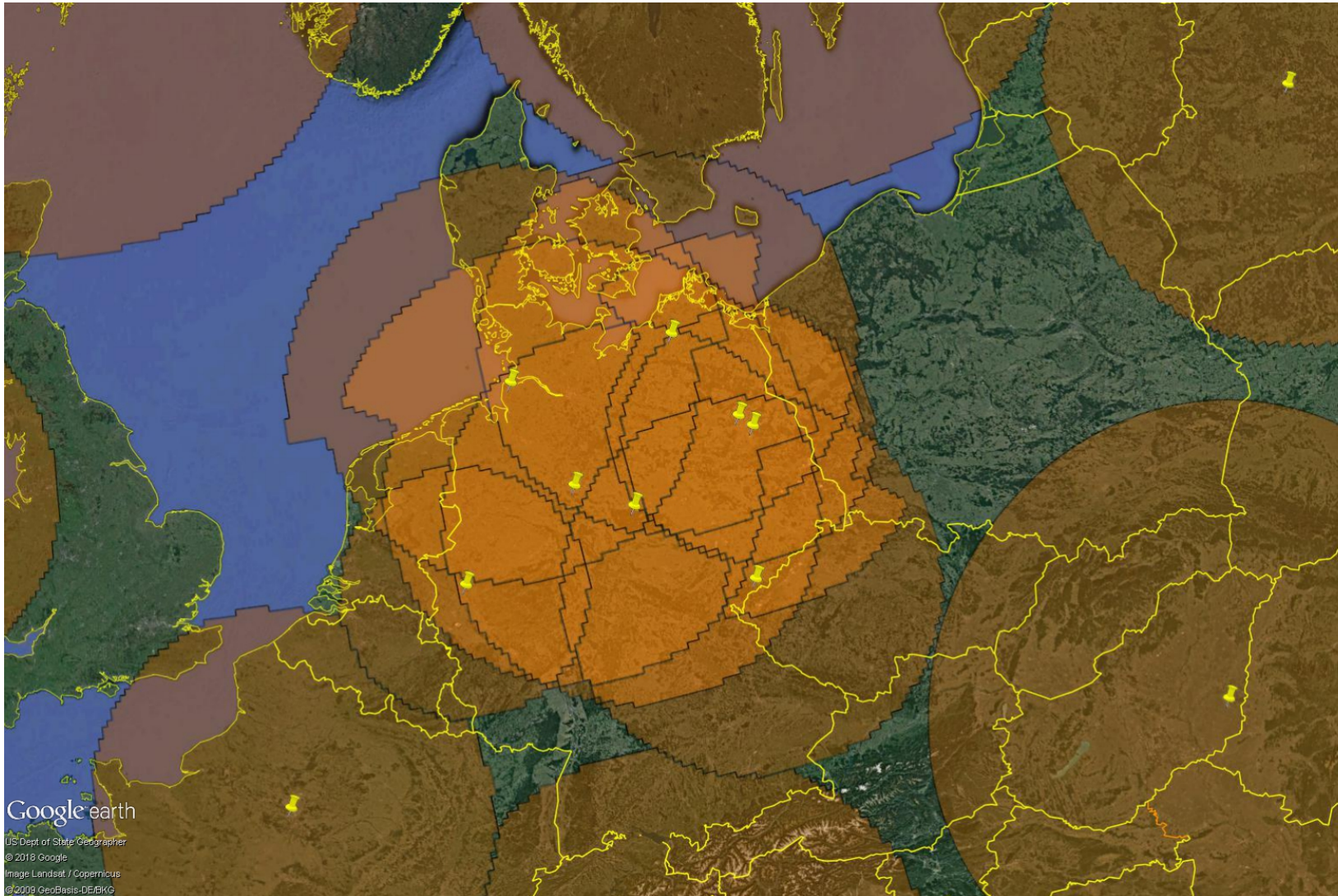
Cluster Principle (1)



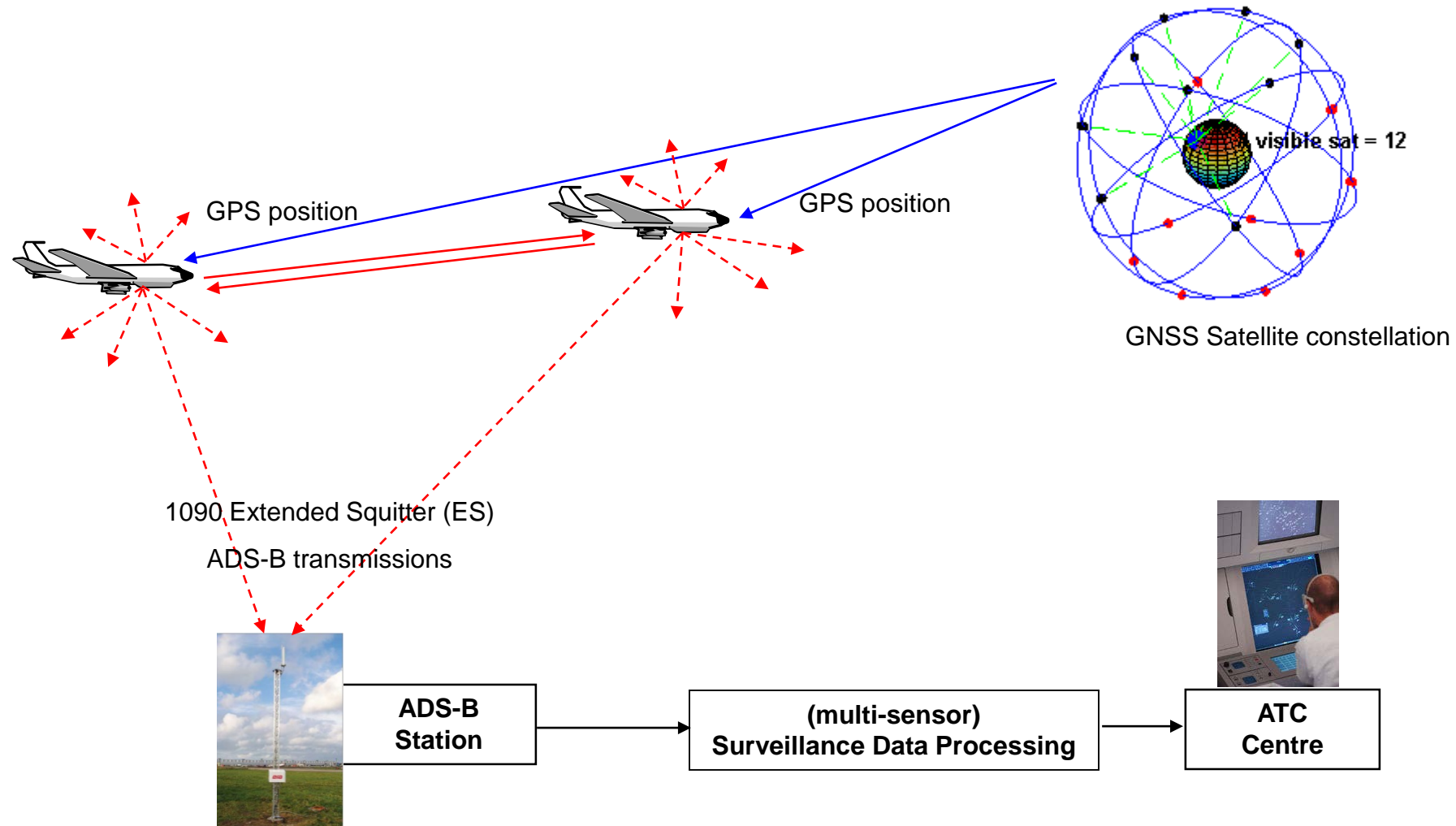
Cluster Management



Example of Cluster



ADS-B : Automatic Dependent Surveillance-Broadcast



ADS-B Extended Squitters

- DF17 Extended Squitters (long Mode S message) broadcasted on 1090MHz by aircraft
- When aircraft is airborne, typically
 - Airborne position – 2 per second
 - Airborne Velocity – 2 per second
 - ACID – 1 every 5 seconds
 - Max 6.2 extended squitters per second
- For vehicles without transponder
 - DF18 Extended Squitter is used to broadcast parameters

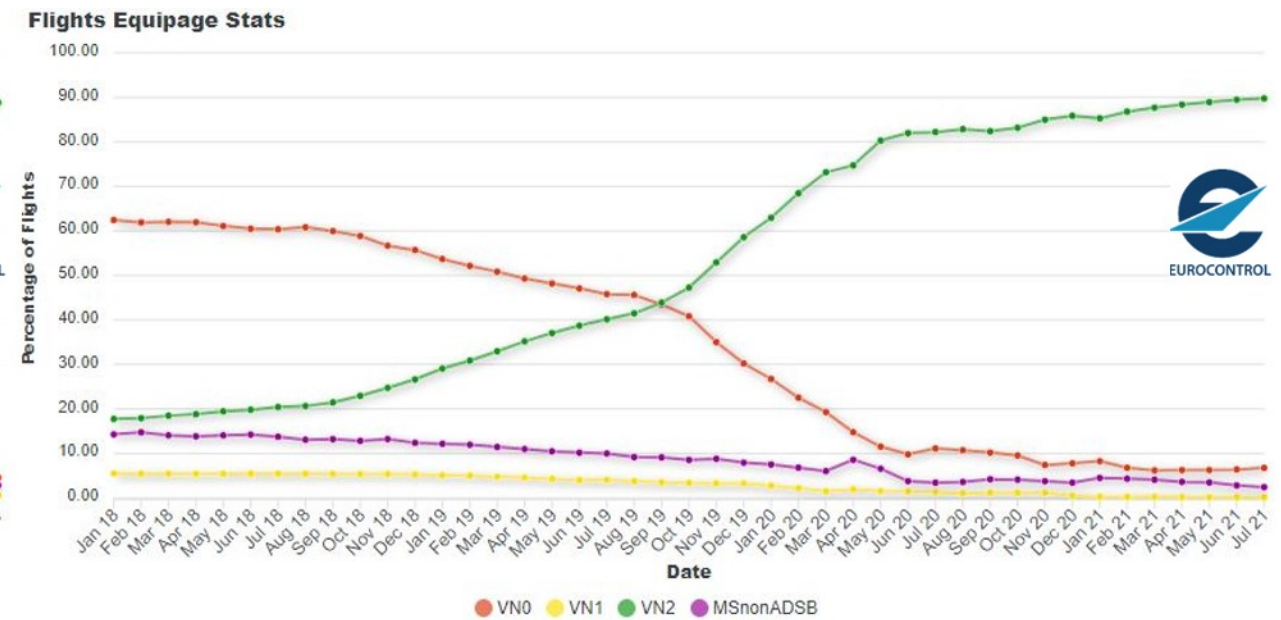
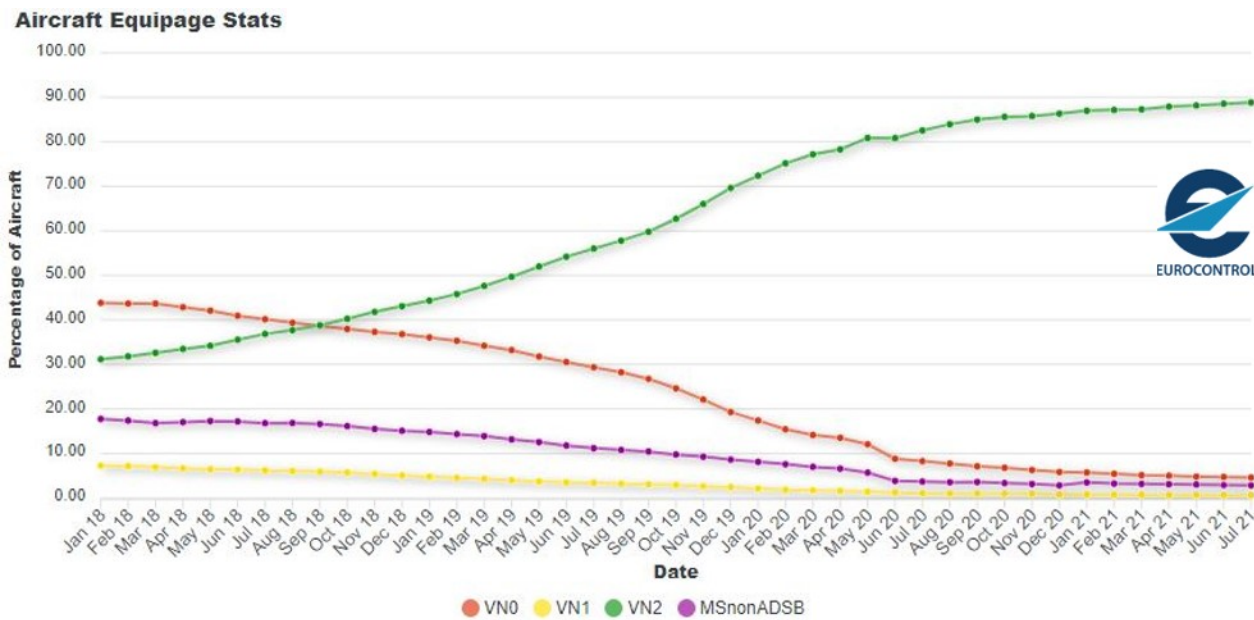
ADS-B Equipage

- Not all aircraft are equipped with ADS-B
- Different versions of ADS-B
 - v0 and v1 have very few quality indicators
 - The position may not be reliable
 - v2 provides good position indicators
- Supported by EU regulation SPI-IR ((EU) 1207/2011 amended by (EU) 2017/386)
 - Mandate ADS-B v2 by 7 December 2020 for IFR >5700kg or Max Speed > 250 knots
 - Smooth retrofitting of the existing fleet
 - ADS-B ground receiver as surveillance layer

ADS-B Airborne Equipage

(b) aircraft with a maximum certified take-off mass exceeding 5 700 kg or having a maximum cruising true airspeed capability greater than 250 knots, operating flights referred to in Article 2(2), with an individual certificate of airworthiness first issued on or after 7 June 1995, are equipped with serviceable secondary surveillance radar transponders that comply with the following conditions:

- Current Aircraft Equipage: **TOTAL FLEET**, under SPI IR
- 1st August 2021 update:
 - Increase to around **88.8%** of aircraft equipped with ADS-B v2, representing around **89.7%** of all NM flights
 - Clear growth deceleration after SPI IR deadline

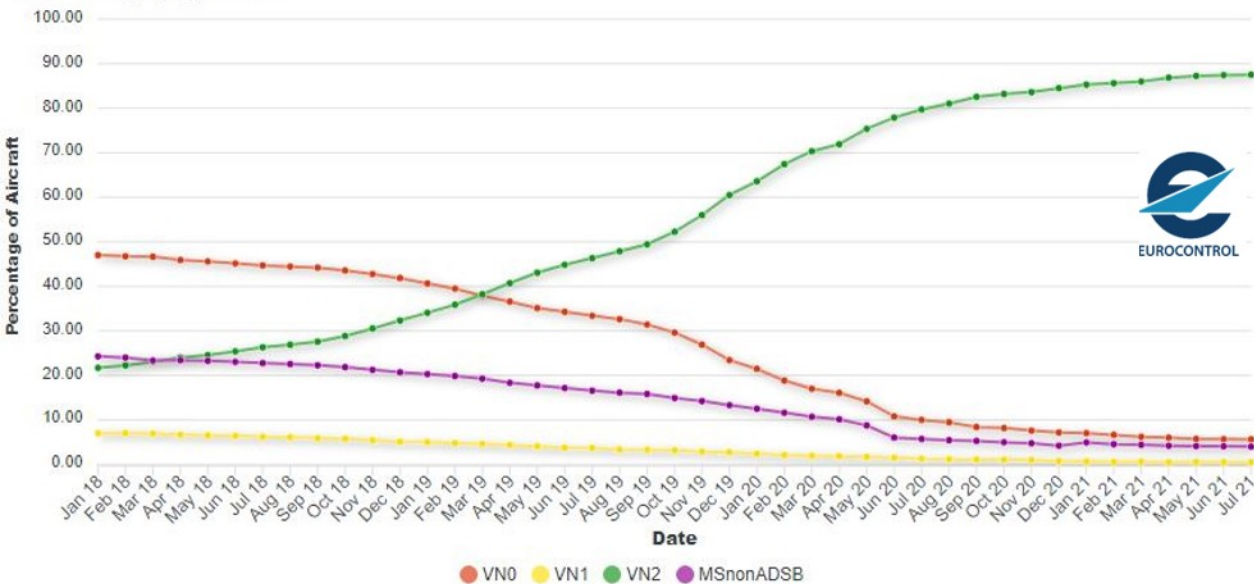


Monthly ADS-B Equipage updates: <https://www.eurocontrol.int/service/adsb-equipage>

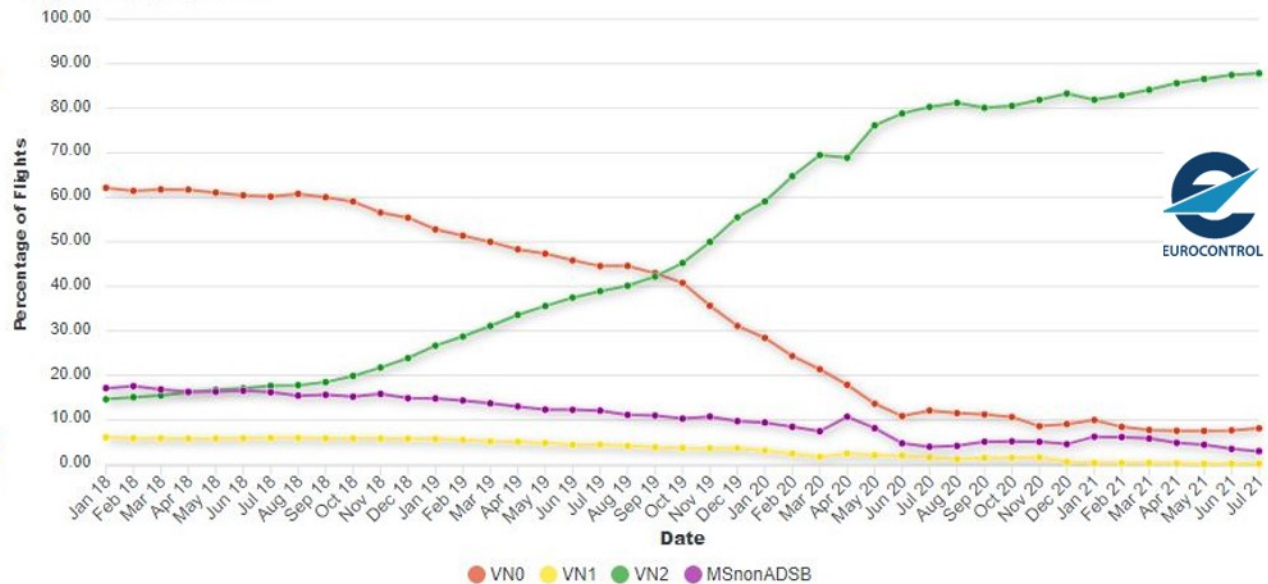
ADS-B Airborne Equipage

- Current Aircraft Equipage: **EU27+4 FLEET**, under SPI IR
- 1st August 2021 update:
 - Increase to around **87.5%** of aircraft equipped with ADS-B v2, representing around **87.9%** of all NM flights by aircraft registered in EU27+4 countries
 - Growth is flattening

Aircraft Equipage Stats



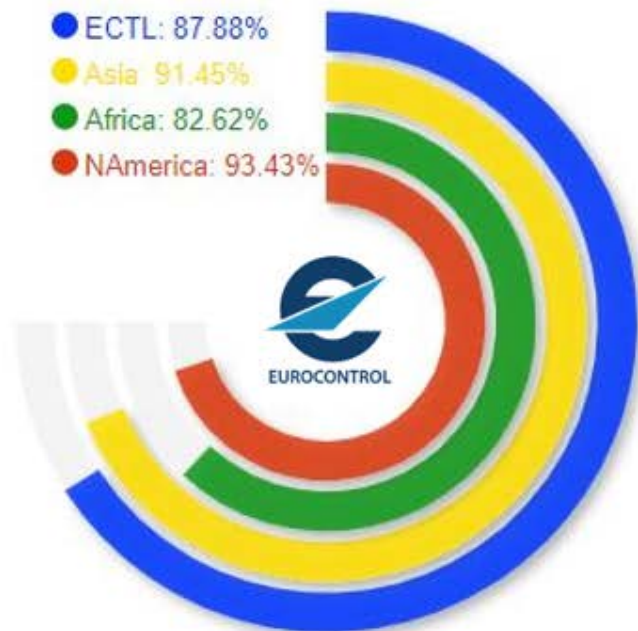
Flights Equipage Stats



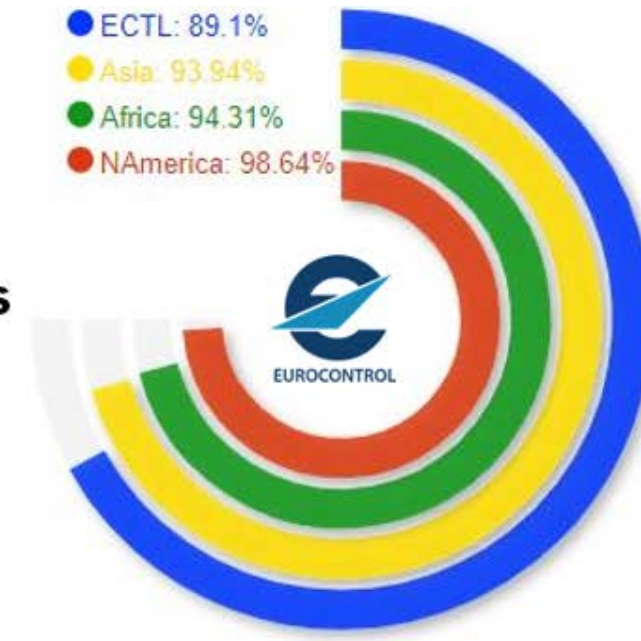
Monthly ADS-B Equipage updates: <https://www.eurocontrol.int/service/adsb-equipage>

ADS-B Airborne Equipage

- Current Aircraft Equipage: **Other fleets**, under SPI IR
- 1st August 2021 update:
 - ADS-B v2 equipped fleet
 - ECTL members ($\approx 88\%$), Asia ($\approx 91\%$), Africa ($\approx 83\%$) and North America ($\approx 93\%$)
 - Non-NM aircraft includes only long-haul flights



Aircraft



Flights

Monthly ADS-B Equipage updates: <https://www.eurocontrol.int/service/adsb-equipage>

Multilateration

- Signal transmitted by aircraft transponder and received at several sensors (Passive)
 - Time Difference of Arrival (TDOA) measurements by ground sensors
 - Central processor calculates aircraft position
- Multilateration is common in Europe
 - Mainly uses squitters for deriving position
 - Short range systems at airport
 - Wide area multilateration systems (WAM), sometimes covering the entire country
- Active interrogation is used by most systems:
 - To extract missing information (e.g. BDS registers)
 - Improved detection of Mode A/C only aircraft
 - Care must be taken
 - not to generate excess 1030/1090MHz FRUIT
 - not to over occupy the Transponder (due to selective interrogations)

MLAT Brno



Station Hranicky

Transmitter antenna

Receiver antenna

GPS antenna

ACAS / TCAS

- Airborne Collision Avoidance System (ACAS)
- Traffic alert and Collision Avoidance System (TCAS)
 - TCAS is an airborne device
 - Requires a Mode S transponder on-board
- TCAS provides collision avoidance protection
 - Traffic Advisories – visual acquisition of intruder aircraft
 - Resolution Advisory – recommended escape manoeuvres in the vertical dimension
- TCAS relies on Acquisition Squitters to acquire aircrafts in vicinity

TCAS Active Surveillance (DO-185B)

- TCAS sends Mode S interrogations (UF 0) to the acquired aircraft (intruder) to get the range, bearing and altitude
- The transponder of the acquired aircraft replies with a DF 0, containing its altitude
- The rate of TCAS interrogations to a Mode S aircraft depends on the range and the closure rate (Time to closest point of approach)
 - Between 1 interrogation every 5 seconds and 1 interrogation per second

TCAS (Extended) Hybrid Surveillance (DO-300A)

- TCAS use DF17 Extended Squitters (ADS-B) to acquire and monitor the aircraft
 - Use valid barometric altitude and position received in DF17 Extended Squitters to acquire and monitor the aircraft
 - Decrease the number of interrogations (UF 0) and replies (DF 0)
 - Depends on data quality and ADS-B Version Number
 - Extended Hybrid Surveillance if ADS-B Version Number ≥ 2
- Extended Hybrid Surveillance (passive)
 - No interrogations when the intruder is far away
- Hybrid Surveillance (low rate of interrogation)
 - Selective interrogations every 10-60s to track intruders when the aircraft get closer (not in near-term collision)
- Once the intruder come close to being a collision threat, it is tracked with active surveillance
- Aircraft not broadcasting DF17 Extended Squitters are tracked actively

DO-300A – Extended Hybrid Surveillance

