Mode S Surveillance Principle

Surveillance/MICA Workshop

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Objective

- Description of the key technical principles of Mode S radar
  - Lockout,
  - Interrogator Code (IC)
    - more details in “Operation on II and SI Code, II/SI Code Operation”
  - Coverage Maps
    - more details in “Mode S Radar Coverage”
  - 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 (24-bit 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 AC)
Mode S and Mode AC Interrogations and Replies

Mode AC and Mode S operate on the same frequencies: Interrogations on 1030MHz, Replies on 1090MHz.
Mode S and Mode AC interoperability

Uplink Pulse Formats (1030 MHz)

<table>
<thead>
<tr>
<th>Name</th>
<th>Mode-AC transponder</th>
<th>Mode-S transponder</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODE A</td>
<td>MODE A</td>
<td>MODE A</td>
</tr>
<tr>
<td>MODE C</td>
<td>MODE C</td>
<td>MODE C</td>
</tr>
</tbody>
</table>

Interrogation Pulse Sequences

<table>
<thead>
<tr>
<th>Mode S Short</th>
<th>Mode S Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁ P₂ P₆ 16.25 µsec</td>
<td>P₁ P₂ P₆ 30.25 µsec</td>
</tr>
</tbody>
</table>

Transponder Replies (1090 MHz)

<table>
<thead>
<tr>
<th>Name</th>
<th>Mode-AC transponder</th>
<th>Mode-S transponder</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODE A ALL-CALL</td>
<td>MODE A</td>
<td>No Reply</td>
</tr>
<tr>
<td>MODE C ALL-CALL</td>
<td>MODE C</td>
<td>No Reply if addressed or All-Call</td>
</tr>
<tr>
<td>MODE S Short</td>
<td>MODE S</td>
<td>No Reply</td>
</tr>
<tr>
<td>MODE S Long</td>
<td>MODE S</td>
<td>No Reply</td>
</tr>
</tbody>
</table>
Mode S radar interrogations

1. **ACQUISITION**
   A Mode S radar sends All-Call interrogations to detect and acquire incoming aircraft:
   - Broadcast interrogations → addressed to all aircraft
   - Aircraft reply with its 24bit Mode S address

2. **SELECTIVE INTERROGATIONS**
   Once acquired, the Mode S radar sends selective interrogations to the aircraft using the 24bit Mode S address received during the acquisition

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.
Aircraft acquisition, selective interrogations and lock-out

- Aircraft not in line of sight of radar or not in power budget → does not receive All-Call interrogations (broadcast)
- Aircraft outside surveillance coverage → receives All-Call interrogations (broadcast) and replies, but replies not processed by radar
- Aircraft acquired by radar in surveillance coverage → 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

Radar Surveillance Coverage
Radar Lockout Coverage
SSR 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
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 and decodes the IC.
   - If it is not locked on this IC, the aircraft replies to the All-Call interrogation (All-Call reply – DF11).
   - The IC of the Mode S radar and the 24bits Mode S address of the aircraft are contained in the All-Call replies.

3. Mode S radar receives All-Call replies containing its own allocated IC
   - Decodes the 24bits Mode S address of the aircraft
   - Computes the aircraft position (range, azimuth)

⇒ The aircraft is acquired
All-Call Format

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

- **UF:5**
- **PR:4**
- **IC:4**
- **CL:3**
- **Spare 16**
- **AP:24**

**UF 11 All-Call Interrogation**

- **UF:5**
- **PR:4**
- **IC:4**
- **CL:3**
- **Spare 16**
- **AP:24**

**PR:** probability of reply + lockout override
**IC** and **CL:** II code or SI code
**AP:** address, Mode S only all-call is 24 * '1' or FFFFFFF

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

- **DF:5**
- **CA:3**
- **AA:24**
- **PI:24**

**DF 11 All-Call Reply**

- **DF:5**
- **CA:3**
- **AA:24**
- **PI:24**

**AA:** Mode S address of the aircraft
**PI:** parity overlaid on the II code or SI code of the interrogator
Stochastic Acquisition and Lockout Override

- **Stochastic Acquisition**
  - Used for acquiring targets close in range
  - Probability of reply in All-Call interrogation

- **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)
Stochastic Acquisition

![Stochastic Acquisition Diagram]

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

Mode S Surveillance Principle
Selective Interrogations and Lockout

- Once an Mode S aircraft is acquired, the Mode S radar knows:
  - 24bit Mode S address of the aircraft
  - Position of the aircraft (range/azimuth)

- The Mode S radar sends selective interrogations to the aircraft using the 24bit Mode S address:
  - Only the aircraft having the correct 24bit Mode S address replies
  - Request Mode A Code or Altitude (Mode C)
  - Lockout request 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.
  - 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

<table>
<thead>
<tr>
<th>UF 4,5</th>
<th>PC:3</th>
<th>RR:5</th>
<th>DI:3</th>
<th>SD:16</th>
<th>AP:24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude Request or Identity Request</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AP: parity overlaid on the aircraft address + II/SI code, lockout and BDS extraction</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>DF 4,5</th>
<th>DF:5</th>
<th>FS:3</th>
<th>DR:5</th>
<th>UM:6</th>
<th>AC or ID:13</th>
<th>AP:24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude Reply or Identity Reply</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AP:24</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Altitude Reply or Identity Reply + BDS</td>
<td></td>
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</tbody>
</table>

DF/20/21 are same as DF/4/5 with a 56 bit data field

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

Note: The Mode S Period is also known as the Roll-Call Period
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). More information in “Radar programming – MIP”

Mode S and Mode AC all-calls can be sent in the same All-Call period
Elementary Surveillance (ELS)

- Basic Surveillance functionality
  - 24-bit technical identification
  - Mode A code
  - Altitude reporting to 25ft (Mode C)
  - 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)
  - Including Emergency situations + SPI
  - SI-Code functionality
ELS Registers

- The BDS registers required for Elementary surveillance are:
  - BDS 1,0 – Data Link Capability Report
  - BDS 1,7 – Common Usage GIICB Capability Report and
  - BDS 2,0 – Aircraft Identification

- The provision of these registers is mandated for all aircraft

- These registers are requested in the first selective interrogations
  - typically 3 selective interrogations in the same beam once the aircraft is acquired

- The content of these registers should not change under normal flight conditions
  - If it does, it should be broadcasted

- EHS register availability known from BDS 1,7
Enhanced Surveillance (EHS)

- 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
If an aircraft is in the cover of several radars, then they could share that information via ground data links.
Cluster Principle (1)

Aircraft replies to All-Call interrogations on IC = x from Radar A and is acquired. Then Aircraft is locked on IC = x.

Aircraft locked by Radar A on IC = x.
Aircraft cannot reply to All-Call interrogations from Radar B on IC = x.

Radar A coverage (surveillance = lockout) IC = x.

Aircraft is selectively interrogated by Radar A in his coverage.

Aircraft is selectively interrogated by Radar B in his coverage.

Radar A provides track support to Radar B for acquisition without All-Call replies.

Radar B coverage (surveillance = lockout) IC = x (same as Radar A).

Mode S Surveillance Principle
Cluster Principle (2)

Radar 1 provides track support to radar 2 for acquisition without All-Call replies
Example of Cluster
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

- 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.
  - Between 1 interrogation every 5 seconds and 1 interrogation per second
TCAS Hybrid Surveillance (DO-300)

- TCAS with Hybrid Surveillance use passive surveillance to track intruders not in near-term collision
  - Use valid barometric altitude and position received in DF17 Extended Squitters to acquire and monitor the aircraft
  - Decrease Mode S surveillance interrogations done by TCAS (UF 0) and replies (DF 0)
  - 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-300 – Hybrid Surveillance

Active surveillance.
Intruder is a near threat in altitude and range.
TCAS active interrogation at 1 Hz.

Passive surveillance.
Intruder is a near threat in altitude or range.
Validate intruder with TCAS active interrogation at 0.1 Hz.

Passive surveillance.
Intruder is not a near threat.
Validate intruder with TCAS active interrogation once per minute.
TCAS Extended Hybrid Surveillance (Future)

- TCAS use DF17 Extended Squitters (ADS-B) to acquire and monitor the aircraft
  - Decrease the number of interrogations (UF 0) and replies (DF 0)
  - No interrogations in Extended Hybrid Surveillance (passive)
  - Depends on data quality and ADS-B Version Number
    - Extended Hybrid Surveillance if ADS-B Version Number ≥ 2
DO-300A – Extended Hybrid Surveillance

Active Surveillance
Intruder is a near threat in altitude AND range.
TCAS active interrogation every 1s.

Hybrid Surveillance
Intruder is NOT a near threat in altitude AND range.
Revalidation of the hybrid surveillance track with TCAS active interrogation every 10-60s.

Extended Hybrid Surveillance
Intruder is NOT a near threat in altitude AND range, ADS-B position data qualified and signal strength is lower than extended hybrid surveillance MTL. No TCAS active interrogations.

Own ship
Resolution Advisory
Traffic Advisory

Increasing Collision Potential
TCAS Resolution Advisory

- In case of Resolution Advisory, long Mode S messages are exchanges for coordination:
  - TCAS interrogations: UF 16
  - Transponder replies: DF 16
ADS-B: Automatic Dependent Surveillance-Broadcast

Mode S Surveillance Principle

1090ES
ADS-B transmissions

GPS position

GNSS Satellite constellation

visible sat = 12
ADS-B

- Broadcast per aircraft of parameters
  - DF17 Extended Squitters (long Mode S message) on 1090MHz
- 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
SUR Equipage per flight over Paris 2018

Flights Only Operating Below FL150:
- Mode S: 45%
- Mode AC: 51%
- ADS-B: 3%
- V0: 0%
- V1: 0%
- V2: 3%

Flights Operating Above FL250:
- Mode S: 9%
- Mode AC: 1%
- ADS-B: 91%
- V0: 70%
- V1: 3%
- V2: 17%
ADS-B Surveillance Equipage Evolution

**ADS-B capabilites per Aircraft and Flights over Paris**

- **Aircraft ADS-B v0**
- **Aircraft ADS-B v1**
- **Aircraft ADS-B v2**
- **Flights ADS-B v0**
- **Flights ADS-B v1**
- **Flights ADS-B v2**
Multilateration

- Signal transmitted by aircraft transponder and received at several sensors
  - Time Difference of Arrival (TDOA) measurements by ground sensors
  - Central processor calculates aircraft position

- Multi-Lateration is common in Europe
  - Mainly uses squitters for deriving position
  - Mainly short range systems at airport
  - Wide area systems are emerging

- Active interrogation is common
MLAT Brno

Station Hranicky
- Transmitter antenna
- Receiver antenna
- GPS antenna
Active Multilateration Systems

- **Independent** of existing infrastructure
- **Improved detection** of Mode A/C only aircraft
- **Complementary** information to position (Mode A, Mode C, A/C ID)
- **Increase accuracy** at long range
- Care must be taken
  - not to generate excess 1030/1090MHz FRUIT
  - not to over occupy the Transponder (due to selective interrogations)