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Principles of Mode S Operation and Interrogator Codes

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Abstract

This document contains a description of the principles of Mode S operation, including selective addressing, Interrogator Codes (II-Codes and SI-Codes), modes of operation and general issues related to Mode S operation. It forms part of the Mode S guidance material developed by the Mode S Programme (www.eurocontrol.int/mode_s/).

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CONTENTS

1. INTRODUCTION

This document is intended to provide some explanations for those implementing Mode S. In the ‘Core Area’ of Europe, an ongoing implementation programme is replacing existing classical SSR interrogators with Mode S ground interrogators, compliant with the EMS (European Mode S) ground station specification *[Ref. 7]*.

The discussion covers the operation of Mode S system only and does not consider the operation of other protocols during the transition between Mode A/C SSR and Mode S surveillance.

This paper attempts to provide a more readable description of Mode S operation than can be found in ICAO Annex 10 *[Ref. 1]* where the functionality to support it is formally specified. In no way should this document be considered to supersede or contradict Annex 10 which is the formal and overriding specification.

The document is intended to provide technical information which will aid understanding of the implementation guidelines as they are published on the Mode S Programme web-site. As guidelines are published, they will refer to certain aspects of this technical discussion rather than repeating the same issues in many documents.

2. ICAO AIRCRAFT ADDRESS & SELECTIVE ADDRESSING

Mode S surveillance protocols implicitly use the principle of selective addressing.

Every aircraft will have been allocated with an ICAO Aircraft Address which is hard coded into the airframe (this was originally known as the Mode S address). There are a number of ways of implementing this but the principle is that each airframe will have it’s own unique address. It is worth noting that a discrete block of codes may be allocated locally for use on surface vehicles at airports (useful for example where A-SMGCS systems are being used).

The ICAO aircraft address consists of 24-bits (therefore 16,777,216 possible codes) and will have been allocated by the registering authority of the State within which the aircraft is registered. Each ICAO Contracting State has been allocated a block of codes that it can allocate to aircraft within it and the number available depends on the relative size of that State and volume of air traffic. The way in which a State allocates codes between civil and military users is an issue for that State only. A block of codes may also be required for airport surface vehicles if they were to be required at airports to support multi-lateration – although this must also be managed by the State on a local basis.

Sizeable unallocated blocks of codes have been reserved for different ICAO regions and over 3 million codes are as yet unallocated to any State or region. With careful management, there should be no shortage of codes, even in the longer term.

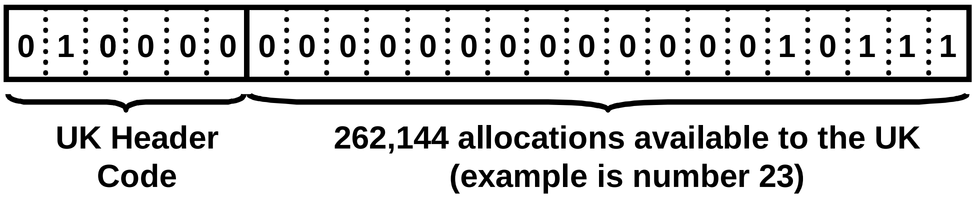

Figure 1. ICAO Aircraft Address

Figure 1 illustrates an example of a code that would have been allocated by the UK. If the first 6 bits of the address are ‘010000’ then this signifies that the aircraft is registered in the UK. The remaining 18 bits comprise 262,144 codes that can be allocated by the UK in whatever manner they choose. The length of the header block, and hence codes, varies by State. For example, Austria has a 9-bit header block which means that it has just 32,768 codes available to allocate.

A State may be allocated a block of codes of the following sizes (See Volume III of *[Ref. 1]*, Appendix to Chapter 9 for full details):

1,024

4,096

32,768

262,144

1,048,576

The ICAO standards state clearly that the ICAO aircraft address should be used only for technical correlation of tracks. Technically, the ICAO aircraft address is fundamental to the operation of ACAS systems as well for use in local radar trackers, multi-radar trackers and system tools such as STCA.

The address ‘0000 0000 0000 0000 0000 0000’ is not a valid address and the address ‘1111 1111 1111 1111 1111 1111’ is a special case address and is known as the all-call address. A transponder will only accept a Mode S interrogation that is sent to the all-call address or is sent to it’s own unique address.

In this way, selective interrogation ensures that one surveillance interrogation elicits one reply from the addressed target.

Note 1: Some other rules exist such as that no aircraft may have more than one address and that addresses must not be changed during flight and may only be changed when an aircraft is sold to an organisation in another State.

The registering authority of the new state must allocate a code from it's block of available codes. A temporary code, allocated by ICAO in exceptional circumstances, may be used in an interim period of no longer than one year.

Note 2: Contrary to an ICAO recommendations, some States have applied an encoding scheme for address allocation, from which, the registration mark of that aircraft within that State can be derived.

Note 3: For security reasons, the military are authorised to change their 24-bit ICAO aircraft address before any flight.

Note 4: Badly programmed addresses can occur and there is an ongoing monitoring process using Mode S ground equipment to identify problem aircraft and inform airlines.

3. ACQUISITION AND LOCKOUT

3.1 Basic Principle Acquisition and Lockout

In order to allow effective operation of Mode S ground sensors with overlapping coverage areas, a discrete identification code, known as an IC (or Interrogator Code), is allocated to each sensor. The IC field is included in all of its interrogations and in every reply that it sent to them. As part of selectively addressed interrogations, the IC is included and this is also included in the reply.

Targets that have been acquired in the all-call period are subsequently selectively interrogated for surveillance information in the Mode S period. Control information within the interrogation allows the ground sensor to apply lockout which means that the target will not reply to an all-call with that IC for a period of 18 seconds. This will be applied by the sensor for all acquired Mode S targets in all areas for which it has responsibility for maintaining lockout.

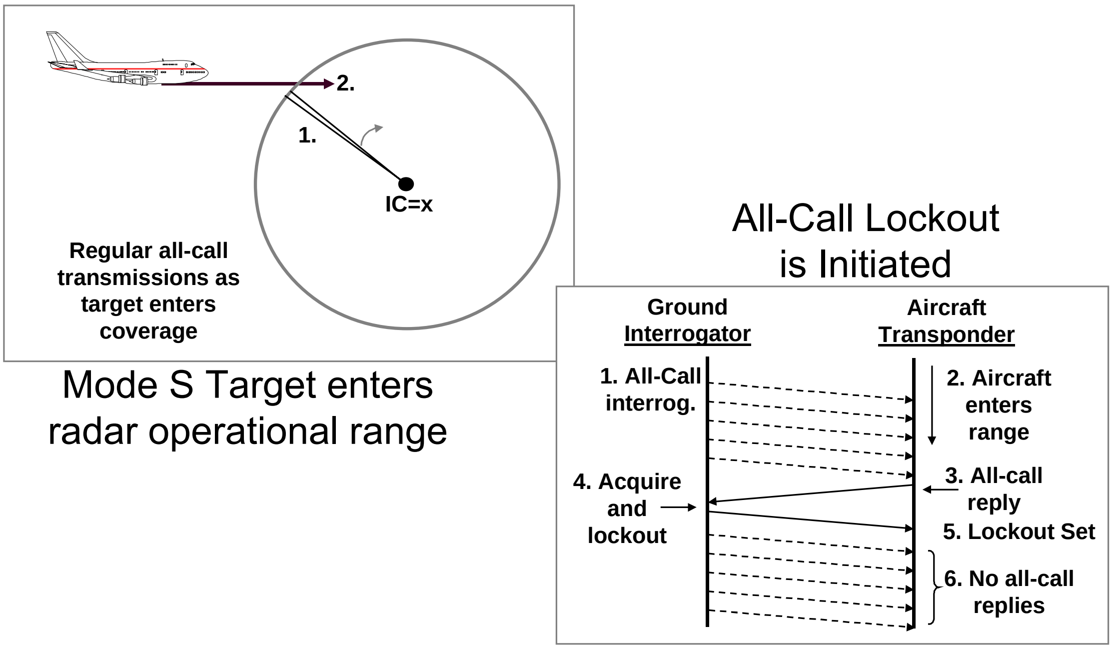

Figure 2. Stages of Lockout

Figure 2 graphically illustrates the sequence of events that occurs when lockout to an interrogator code is initiated.

1. The Mode S interrogator (IC=x) rotates clockwise sending all-calls during the all-call periods. At point 1, the target shown has not yet entered coverage and no replies are received.

2. Aircraft enters sensor coverage and receives all-call interrogation (containing IC=x in a control field).

3. Aircraft transponder generates all-call replies containing sub-fields with the 24-bit ICAO aircraft address and the IC that was in the original received interrogation.

4. The ground sensor receives the all-call reply and decodes the aircraft address and position and has now 'acquired' the target. It then sends selective interrogations during following roll-call periods.

5. The selective roll-call interrogations contain control information that instructs the transponder to disregard further all-calls from all sensors using that IC.

6. The transponder will then ignore all-call interrogations from all sensors using IC=x for a period of 18 seconds. The sensor will normally reset the lockout timer with all selective surveillance interrogations, hence ensuring that all-call lockout is assured throughout as the target travels through the coverage of the sensor.

Of course, ground sensors continue to transmit Mode S only all-call interrogations during the all-call period in order to acquire new aircraft that enter the coverage of that sensor.

3.2 Stochastic Acquisition

Stochastic acquisition is a technique used during the all-call period to acquire closely spaced (in slant range) targets entering coverage (Note: stochastic is a term meaning 'probabilistic'). All-call interrogations can be sent with a probability of reply weighting built into them. The weighting can be a probability of reply of 1, ½, ¼, 1/8 or 1/16.

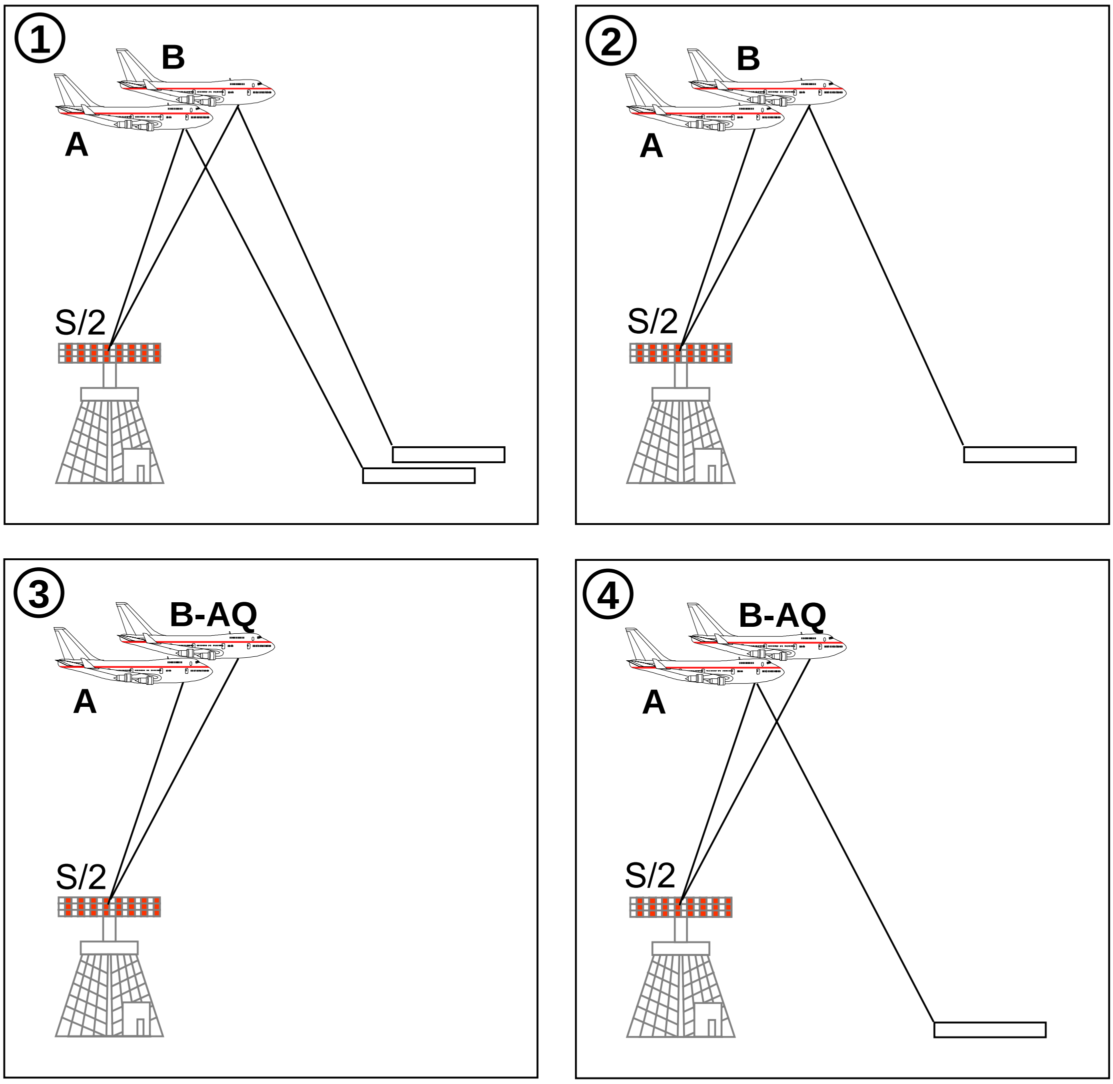

Figure 3. Stochastic Acquisition

Figure 3 illustrates the principle of stochastic acquisition of two targets that are closely spaced in slant range (although they may be at quite different heights) with a Mode S sensor sending all-calls with a 50% probability of reply in each all-call period (this example assumes that each box is an all-call period in the same antenna revolution):

> All-Call S/2 50% PR issued. Aircraft A and aircraft B receive it. Aircraft A and Aircraft B both reply (both examined 50% probability and decided to reply). The replies overlap in time at the ground receiver and the de-garbling processes were unable to decode them so both replies were lost.
>
> All-Call S/2 50% PR issued. Aircraft A and aircraft B receive it. Aircraft A decides on a 'No Reply' (50%) and aircraft B replies. Aircraft B is then selectively interrogated and locked out.
>
> All-Call S/2 50% PR issued. Aircraft B is locked out and ignores the interrogation. Aircraft A decides on a 'No Reply' (50%). No replies sent.
>
> All-Call S/2 50% PR issued. Aircraft B is locked out and ignores the interrogation. Aircraft A decides to reply (50%). Aircraft A is then selectively interrogated and locked out. Both targets are now locked out to the ground sensor.

It is possible that both targets in the example could have been closely spaced in slant range for several antenna revolutions. Without stochastic probabilities of reply, it is possible that neither of them would be correctly acquired since the replies may have been overlapping in time and not effectively de-garbled. Clearly not a desirable situation.

Although it is perfectly possible that targets are acquired and locked out during a single antenna revolution, It is likely to take more than one antenna revolution to complete this process. E.g. POEMS evaluation was over 3 antenna revolutions, with the first revolution receiving the all-call reply, the second revolution, starting selective roll-call interrogations and then in the third revolution, starting to reset lockout to the target.

3.3 Lockout Override

In order to allow an interrogator to operate without co-ordination with it's neighbours, the Mode S protocols allow the interrogator to force a transponder to reply to all-calls, regardless of the current lockout status to that interrogating IC (i.e. lockout is overridden). This method is known as 'lockout override'. In addition, in order to avoid garbling problem as explained in the section related to stochastic acquisition, it is recommended that lockout override is applied with a Probability of Reply value of less than 1.

Possible stochastic values for the PR (Probability of Reply) field in an all-call interrogation are 1, ½, ¼, ⅛ and 1/16 which is the same as for standard stochastic acquisition (and can also be applied in 11.25º azimuth sectors (1/32 of a revolution). If applied in an all-call interrogation, a target that is already acquired by IC=x and locked out by it as well could elicit an all-call interrogation from it.

Stochastic lockout override acquisition (SLA) might be used in coverage areas where there is some overlap with at least two sensors using the same IC and not communicating as a cluster (example is provided in Figure 4). It is also highly appropriate in all areas as a supplementary acquisition check. It may perhaps be useful in areas near coastlines in case some form of vessel (e.g. a ship) arrives within coverage from another region and is still using a code that would conflict with the European allocation. Finally, supplementary acquisition techniques may also be useful for coverage reconfiguration scenarios when a cluster node or link fails (see cluster operation).

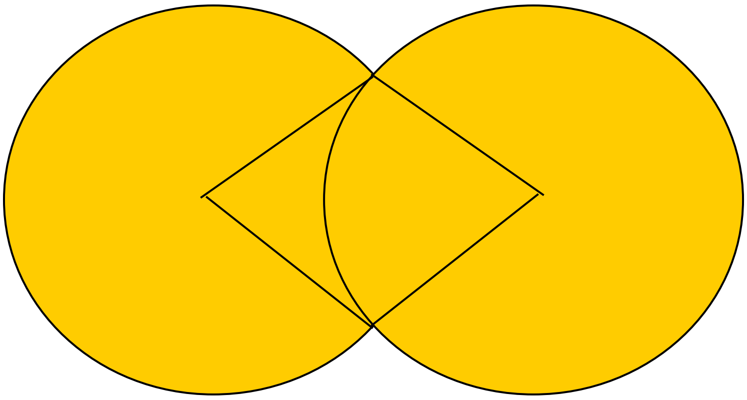

Figure 4. Stochastic Lockout override Acquisition (SLA)

3.4 Intermittent Lockout

Intermittent Lockout is another mechanism with which lockout between two or more sensors that are using the same IC but are not operating as a cluster can be managed.

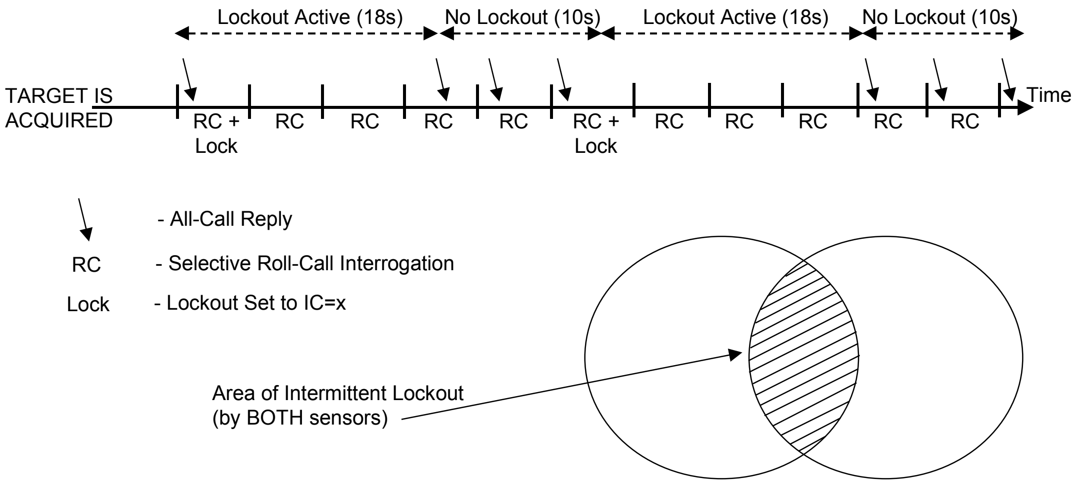

Figure 5. Intermittent Lockout

Figure 5 illustrates the concept of intermittent lockout with the example. The intermittent lockout is applied to targets in coverage cells that have at least some part within the shaded zone (assume both interrogators are operating with the same IC).

The principle is straightforward. This effect is managed through effective management of the Roll-Call period (RC) rather than the All-Call period used in other supplementary acquisition and lockout management techniques.

All interrogators having acquired the aircraft will not lockout the aircraft until they receive all-call replies. Interrogators will wait for a further period of time before resetting lockout on an aircraft (the example shows the recommended period of 10s). The period of time during which the interrogator does not lockout the aircraft shall be long enough to allow other Mode S stations in coverage of that target with the lowest rotation speed to acquire the aircraft.

One of the interrogators will acquire and lock out the target for a short period (minimum lockout period is 18s as per Annex 10) during a roll-call period once it enters or nears the shaded zone. In the example, the antenna is roughly rotating at 5s per antenna revolution. Therefore, lockout remains active to IC=x for 18s which in the case of the example is in the 4th revolution. The sensor has not reset lockout during that period. If not already acquired through stochastic and override techniques, the other sensor will then be able to acquire the target. The original sensor will wait a further period of 10s after the 18s lockout expires before setting lockout on that target again. Of course, the second sensor may itself have set intermittent lockout by that stage.

In principle, any number of overlapping interrogators using the same IC should be able to operate effectively using this principle. One drawback of this method however is that both (or more!) of the sensors involved have to be playing the same ‘game’ and applying this interrmittent lockout in the same way in the same coverage regions.

3.5 Supplementary Acquisition and Temporary Lockout

Supplementary acquisition is the term used to describe operation using temporary lockout to II-Code=0 (one single lockout command issued). Annex 10 describes this operation as a method of acquiring targets that may not have been detected. It allows for a target to be locked out to II=0 ‘for a short period’. This minimum period would be 18s (the duration of the lockout timer). This allows for further acquisition activities but needs to be carefully managed if other interrogators, using completely separate ICs, with areas of overlapping coverage were to use the same technique.

4. MODE INTERLACE PATTERNS

There is a careful balance between the reliable acquisition of all targets and the potential of flooding the RF environment with unwanted replies to acquisition interrogations. It is necessary to choose an appropriate Mode

Interlace Pattern (or MIP) to manage the acquisition activities to ensure minimal interference.

4.1 All-Call and Roll-Call Periods

In order to provide surveillance of both Mode A/C and Mode S equipped aircraft with minimal mutual interference, the uplink RF 1030MHz channel is ‘time-shared’ between all-call activities and roll-call activities. The channel time is divided into distinct and non-overlapping periods of:

Mode A/C and Mode S activity, known as the ‘all-call period’ and

Mode S selective interrogation activity, known as the ‘roll-call period’

During the all-call period, interrogations are sent to perform surveillance of Classical SSR equipped Mode A/C aircraft and to ‘acquire’ new Mode S aircraft (acquisition of the 24-bit ICAO aircraft address and the position of the aircraft).

During the roll-call period (also sometimes known as the ‘Mode S period’), selective surveillance interrogations are sent to Mode S aircraft. Once an aircraft has been acquired during the all-call period, surveillance is then carried out uniquely during the roll-call period. During the roll-call period, lockout may be continually reset by the interrogator to its own IC, by setting control information as part of selective surveillance interrogations.

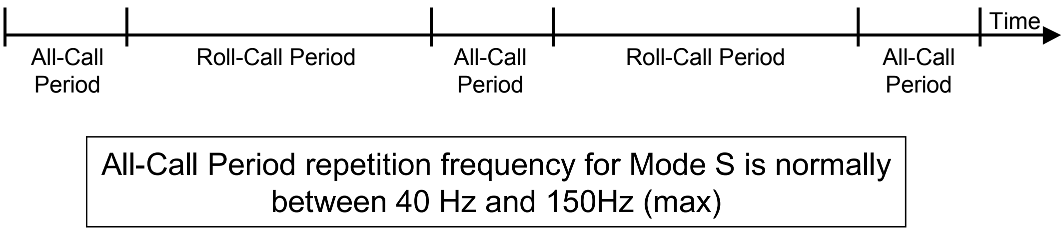

Figure 6. All-Call and Mode S Periods

Figure 6 illustrates that an all-call period normally has a Mode S period directly after it and this normally repeats with a frequency of anywhere between 40Hz and 150Hz (the stated ICAO maximum is 250Hz). The repetition frequency and duration of the All-Call period is a local implementation issue. The exact duration of either period will depend on the characteristics of the system such as the antenna revolution rate, the beam-width and the maximum range. There will normally be several all-call periods (and hence roll-call periods as one will always follow the other) available to interrogate all targets in range during one revolution.

Note: During a transitional mixed Mode A/C / Mode S environment, the idea is to have enough all-call periods in one beam dwell to have at least 4 Mode A/C interrogations (2 per mode). This ensures an acceptable probability of detection and code validation for Mode A/C equipped aircraft.

During the all-call period, targets will normally be interrogated with classical SSR interrogations (Intermode, with a 'short P4' which inhibits Mode S aircraft from replying) and with Mode S only all-call interrogations with the ICAO aircraft address of '1111 1111 1111 1111 1111 1111' (aircraft reply with their own 24-bit ICAO Aircraft Address).

All Mode S aircraft in the beam that receive this interrogation would normally send a reply. However, this would cause a flood of garbled and lost replies at the ground receiver and other problems for the RF environment.

This issue of all-call FRUIT and garble is resolved through the use of the lockout principle as well as stochastic (probabalistic) acquisition and an ability to override lockout already set. The derivation of the most suitable MIP (Mode Interlace Pattern) is an important issue and normally derived on a local site by site basis to ensure the most effective acquisition performance.

It is noted that a Mode A/C and a Mode S interrogation may be issued during the same all-call period (this will be the scheme adopted in initial implementation phases).

4.2 What Is A MIP?

Mode Interlace Patterns (MIPs) define the sequences of all-call interrogation types that might be made during cycles of all-call periods. Every sensor (or type of sensor) is likely to have different needs and hence different ways of operating.

A simple example of an MIP is shown in Figure 7.

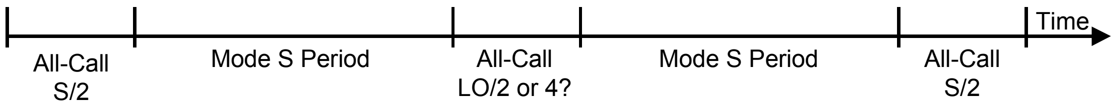

Figure 7. Simple Example of MIP

Note: LO = Lockout Override, S/2 = Stochastic Probability of 0.5.

Note: ICAO Annex 10 (Volume IV 3.1.2.5.2.1.1) defines the stochastic and lockout override functions in the PR (Probability of Reply) field in every all-call. Values of PR from 0 to 4 represent, stochastic probabilities of 1, ½, ¼, 1/8 and 1/16 respectively. Values of PR from 8 to 12 represent stochastic probabilities also of 1, ½, ¼, 1/8 and 1/16 respectively but with lockout override active.

During the all-call period, the following all-call types could be sent in a cyclical manner from one all-call period to the next by a Mode S ground interrogator:

Mode A/C only (not preferred)

Mode A/C only with short P4 (i.e. Mode S targets do not reply). Note: The Long P4 strategy is not recommended by ICAO because of potential adverse effects on the RF environment.

Mode S only all-call

Mode S only all-call with stochastic probability (e.g. S/2 or S/4)

Mode S only all-call with stochastic lockout override probability (e.g. S/2 or S/4)

Mode S only all-call with II=0, issued stochastically (and potentially locked out for a short period)

Etc.

Different cyclical strategies might be more appropriate in different azimuth sectors or even from one antenna revolution to the next.

4.3 Defining A MIP

The default objective is to define a MIP which effectively detects and performs surveillance on classical SSR Mode A/C aircraft using Mode A/C interrogations which also detects and acquires Mode S aircraft using Mode S interrogations. The MIP is constructed in order to separate Mode A/C and Mode S all-calls from Mode S selective (roll-call) activity.

For Mode A/C aircraft, it should be foreseen that at least two interrogations per mode (4 in total) are made while the aircraft is in the main beam of the interrogator. It could perhaps be more than 2 per mode per beam but the trade off is the preference to retain additional roll-call period time to conduct selective Mode S interrogation activity.

A typical ratio is:

1/3 of the time for Mode A/C and Mode S only all-call activity and

2/3 of the time for selective Mode S roll-call activity

However, clearly the exact ratio is very much an implementation issue and will be configured at the station to suit the local requirements and environment.

It is a useful idea to keep the number of roll-call periods equal to the number of all-call periods in order to support a number of possible activities. For Mode S re-interrogation in the beam, the Mode S scheduling function can have some time (during the all-call period) during which it could reschedule failed interrogations for the next Mode S period. However, in some implementations, it is possible to extend or concatenate Mode S periods.

Having defined the characteristics of the all-call and roll-call periods, it is possible to define the Mode A/C interrogation in each of the all-call periods. As the objective is to detect classical SSR equipped aircraft using Mode A/C interrogations as shown in Figure 8. P1, P3 and short P4 is the mode that will be used.

Note: By default, a multisite scenario with non-zero ICs will be employed and the possible adverse effects of increased FRUIT and garbling through using this mode are avoided.

Note: Uplink interrogations 1030 MHz consist of a number of pulses. These are defined in ICAO Annex 10 as P1, P2, P3, P4, P5 and P6. The time spacing and presence of these pulses defines the type and content of an interrogation. P4 is used as part of intermode all-call interrogations and has two forms. A short P4 (P4S) lasts for 0.8 s and forces a no reply from Mode S equipped aircraft whereas a long P4 (P4L) lasts for 1.6 s and elicits Mode A/C replies from Mode A/C equipped aircraft and Mode S only all-call replies from Mode S equipped aircraft. ICAO standards recommend that the P4L strategy is not used as it could have serious adverse effects on the RF environment.

In addition, the Mode S station shall acquire Mode S equipped aircraft using Mode S only interrogations using P1, P2 and P6. This is illustrated in the Figure 8.

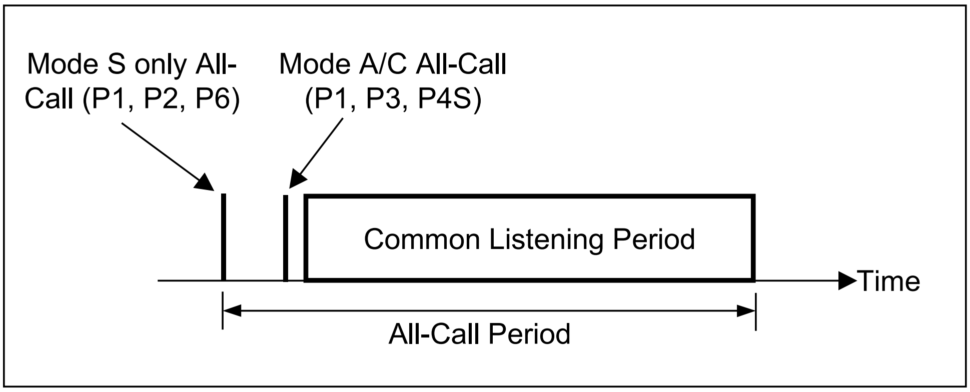

Figure 8. Example All-Call Period

Figure 8 provides a workable solution as the time taken to process and reply to Mode S interrogations (128 microseconds) differs from that of Classical SSR transponders to a Mode S (3 +/- 0.5 microseconds). The common listening period will receive classical SSR replies (Modes A and C) and Mode S only all-call replies (DF=11).

The received signals will be processed by two separate reply decoders within the station, one to process the desired classical SSR replies and one to process the desired Mode S only all-call replies.

Figure 9 illustrates how the transmissions are likely to be sent for mixed mode operation. The Mode S only all-call lasts for just over 20μs and the reply is generated by the transponder 128µs after the sync phase reversal in the P6 pulse. The Mode A/C all-call lasts between 8.8µs (Mode A) and 21.8µs (Mode C) with the reply generated 3µs after the leading edge of the P3 pulse.

Point one in Figure 9 illustrates the sync phase reversal within the P6 pulse, from which timing, the reply will be generated 128µs later. Point 2 illustrates the start of the common listening window. Because of the P1 and P2 of the Mode S only all-call, classical SSR transponders will be suppressed for a period of 35µs +/- 10µs which means that they will ignore the remainder of the Mode S only all-call but will have recovered in plenty of time to correctly receive the classical SSR interrogation. Sending a P4S with the classical SSR interrogation inhibits Mode S aircraft from replying.

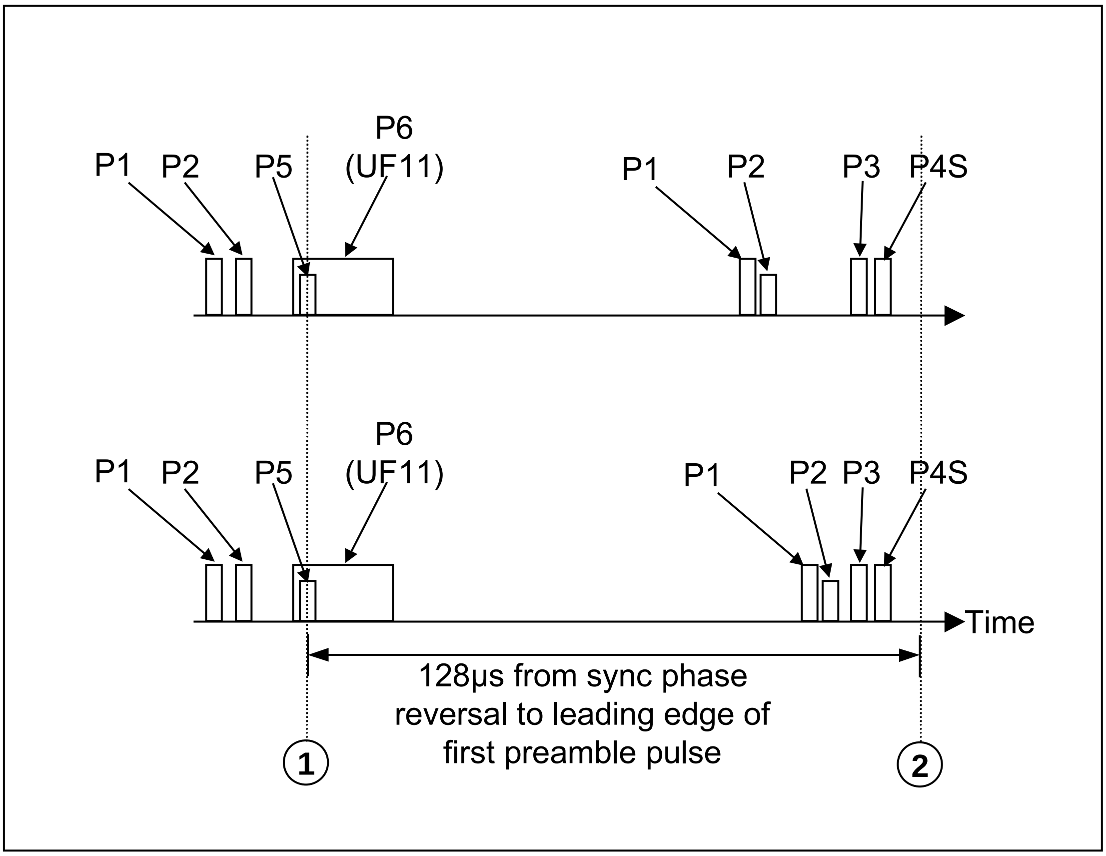

Figure 9. Combination of Mode S and Mode A/C in Same All-Call Period

Therefore, a Mode S equipped aircraft will receive Mode S only all-call and Mode A/C, the Mode A/C interrogation and the listening period will be the same. The figure illustrates two different possibilities one example with a Mode C interrogation being transmitted slightly earlier than the Mode A interrogation would be.

Since there will be at least 4 all-call periods per beam dwell, this is normally more than sufficient to ensure probability of detection (including code validation) requirements are met for both classical SSR targets and Mode S SSR equipped targets. It is possible to further optimise the Mode S only all-call characteristics, for example with a stochastic probability of reply of 0.5 as every second all-call interrogation. This is a very basic MIP but workable and is illustrated in Figure 10.

S only, PR=1 + Mode A , P4S	S only, PR=0.5 + Mode C, P4S	S only, PR=1 + Mode A , P4S	S only, PR=0.5 + Mode C, P4S

Figure 10. A Basic All-Call MIP

Applying stochastic probabilities to all-call acquisition MIPs, allows for improved acquisition of targets entering coverage that are closely spaced in slant range (see stochastic acquisition) whilst also ensuring rapid acquisition of non-garble aircraft entering coverage through the use of interrogations with a 100% probability of reply.

Note: The use of PR in the above discussion refers to the probability that a reply will be generated (e.g. 0.5 or 50%) and not the value (as explained earlier) of the PR field in every all-call interrogation.

More complex MIPs than the basic stochastic MIP described above could be used to resolve particular issues and problems such as:

Adding a stochastic lockout override requirement in some all-call periods to assure full acquisition (under study and investigation at the time of writing);

Working in triple mode in the same beam dwell. For example, to incorporate military interrogation requirements at the same station or to better interlace AC and 1C from antenna revolution to the next;

Define a MIP allowing simultaneous detection of aircraft in Mode A/C and Mode S.

For military users, the modes of interrogation used may be interlaced from one antenna revolution to the next to allow for the extraction of various civil and military modes.

The cyclic MIP patterns used in one azimuth sector may be suitable for the expected traffic in that sector but an entirely different MIP might be required for another for optimal performance. This is a 'next step'

4.4 An Interim MIP

At the stage of POEMS evaluations, there was a transponder fleet in place, with at least one known transponder which did not reply correctly to some Mode S only interrogations. Therefore, it could remain undetected if only Mode S only all-calls and A/C with short P4 were used in the MIP.

Figure 11 illustrates a MIP that was developed and proposed to cope with transponders of this type.

Note: Validation and assessment of the viability of this MIP is ongoing.

S only, PR=1 + Mode A , P4S	Mode C, No P4 (all reply)	Mode A, No P4 (all reply)	S only, PR=0.5 + Mode C, P4S

Figure 11. An Interim MIP

Clearly, the use of standard classical Mode A and Mode C interrogations within the MIP ensures the full detection. Transponder manufacturers had a software fix available very quickly to cure the problem, but a number of outstanding transponders continue to operate as they were not legally required to implement the change until the Mode S State mandates came fully into force.

5. INTERROGATOR CODES

Each sensor should be using an allocated Interrogator Code (IC). In Europe, a centralised IC allocation office, co-ordinated by EUROCONTROL, is in place to deal with requests a derive valid allocations. The administrative part of the allocation process is clearly documented *[Ref. 2]*.

Note: There is also a mode of operation defined in Annex 10 which allows for the "Mode S operation without an assigned Interrogator Code". This assumes operation using stochastic lockout override for acquisition and selective interrogations with control fields pre-specified in order to prevent any lockout conditions being modified.

The use of all-call lockout to control the RF environment works most effectively when no sensors, using the same IC, overlap in coverage areas where they are responsible for maintaining lockout on targets. If this were the case, the sensors would need to be interconnected and communicating between each other to ensure that effective lockout to IC=x is maintained and all of the tracks were acquired by both interrogators.

Within the limits of ICAO Annex 10 specifications, there are a limited number of available ICs available. These are of two types:

16 II-Codes (Interrogator Identifier Codes) are available, 15 of which allow 'multisite operation', using all of the Mode S protocols and

63 SI-Codes (Surveillance Identifier Codes) which function in the same way as II-Codes for lockout purposes (only a few bits added to increase the number of codes). However, the addition of this functionality limits the range of air-ground protocols that can be supported by a ground interrogator using an SI-Code. In addition, a functional SI scenario

requires that a high percentage of the aircraft fleet is fitted with 'SI capable' transponders. SI-Code ground sensors are fully able to support the protocols required by the Elementary (ELS) and Enhanced Surveillance (EHS) applications. The periodic extraction of 'dataflash' information is not possible for ground interrogators using an SI-Code (this is a proposed extension to the EHS application to broadcast infrequently updated parameters on change only).

A Mode S transponder may be locked out to many different ICs simultaneously (in fact, up to 79 ICs if it is SI-Code capable).

In terms of European Mode S system implementation, the regulatory situation means that it will initially be possible only to allocate and use II-Codes. As Mode S implementation continues, in some areas where there are many radars covering very high density areas of airspace, 15 allocatable II-Codes is unlikely to be enough to support allocation of a code to every sensor and having no overlapping coverage areas with another sensor using the same II-Code.

SI-Code functionality (Amendment 73) was developed and formally approved in 1997. The mandatory schedule at the time of writing foresees the availability of SI-Codes by 31st March 2005 but an effective and efficient interim allocation mechanism, using only II-Codes, is required before this date.

The allocation of ICs to interrogators is a complex subject. The derivation of the most efficient allocation plan is an NP-complete problem and involves the use of advanced graph theory techniques to be most efficient. Additional factors complicate the issue, including the fact that lockout responsibility for a sensor is based on a coverage map sectorised to cells of approximately 5NM x 5NM. Operational requirements and constraints on a sensor by sensor basis, civil / military issues and the fact that up to 6 sensors could be interconnected (known as a 'cluster') and operate using just one IC will also affect and complicate the allocation process.

Note: The cell size is around 5NM x 5NM around the latitude of Paris (around 50 degrees North). Cell size will be less than this at Latitudes North of Paris and larger at Latitudes South of Paris.

Note: NP-Complete stands for Non-deterministic Polynomial – Complete and refers to a problem where the number of possible solutions is exponential with the number of, in this case sensors, in the scenario.

Dedicated computer-based modelling tools will be required to support the allocation process and the generation of coverage maps for each sensor.

II-Code=0 is a special case II-Code (known as the non-selective II-Code). The protocols and principles of operation using II-Code=0 are slightly different from that for II codes 1 to 15 (which use multi-site operation).

Operation based on lockout override for interrogators without an assigned interrogator code should not be confused with operation using II-Code=0.

Once aircraft acquired using the stochastic acquisition technique, operation without an assigned IC is defined in such a way that subsequent selective interrogations cannot modify any existing lockout conditions. It is likely that some military organisations will use this method of operation.

Multisite operation refers to a scenario where interrogators overlap in coverage but using discrete ICs in those areas. Multisite operation is foreseen for use in Europe (for fixed position ground interrogators). This requires that overlapping sensors operating independently of each other will have their own IC.

Finally, implementation plans are reasonably well defined but tend to be modified and adapted as time goes on. This makes the allocation process even more complex when new allocation requests are being received on a sensor by sensor basis. The allocation procedure should be able to cope into at least the medium-term future without requiring that all sensors coverage responsibility is reallocated.

There are 6 distinct categories of interrogator that have been defined and their requirements for an IC are likely to differ.

> Fixed surveillance sensors used for ATC (all static sensors configured for civil/military ATC service)
>
> Fixed Surveillance sensors used for air defence (all static sensors configured for air defence)
>
> Deployable sensors (temporary installations, including long range weapon systems)
>
> Mobile Military sensors (mobile military radar operating while moving, apart from airborne early warning systems)
>
> Airborne Early Warning systems (airborne mobile radar similar to the AWACS type)
>
> Active multi-lateration systems (fixed system based on multiple receivers / transmitters with a very short range)

It is possible that an interrogator may be allocated more than one IC and may use different codes in different situations (e.g. in different azimuth sectors). However, the complexity of the system increases when this sort of function is implemented.

6. COVERAGE MAPS

The EMS uses a set of pre-defined coverage maps. An EMS sensor is able to use 3 separate coverage maps at any one time as well as to operate as a cluster of up to 6 stations. The three maps will define areas of responsibility for:

lockout

surveillance and

datalink

The coverage maps are defined in considerable detail in the EMS Coverage Map interface control document (ICD) *[Ref. 3]*. All sensors must be able to use and apply coverage maps in the ICD format.

6.1 Coverage Cells

The coverage of the station is broken down and delimited as cells with components defining their size in both the horizontal and the vertical planes.

In the horizontal plane, the coverage maps contain cells delimited by Lat/Long boundaries (ΔLat=0.0833º and ΔLong=0.1253º) and are not strictly Cartesian. The size of each of these coverage cells is nominally about 5NM by 5NM in size. This refers to the approximate size of the cells at the same Latitude as Paris (Approximately 50º North). It is worth noting that this cell size in Lat/Long has been used for Europe but that other cell size constants may be considerably more appropriate in different regions of the world.

The World Geodetic System 1984 (WGS 84) geodetic reference model of the Earth is used. It is an earth fixed global reference system, including an earth model that has some assumed parameters such as the shape of an earth ellipsoid, its angular velocity, and the earth mass which is included in the ellipsoid reference. WGS 84 was developed to harmonise the often conflicting geodetic networks and reference frames of the States. For more information, see www.wgs84.com.

When defining coverage maps, a common origin point for the 'ICAO European Region Coverage Zone' is recommended for coverage map initiations which ensures that overlapping cells can fit exactly onto each other. The recommended origin has a Longitude of 15W and Latitude of 42 degrees North.

There is also a vertical component to the coverage cells. Each responsibility cell will have been allocated a Minimum Altitude and a Maximum Altitude. This is defined in steps of 200ft and for a radar station, this is referenced to the Barometric Pressure Altitude (Mode C or Pressure Altitude reported to a standard pressure of 1013.25 hecto-pascals or millibars) reported by aircraft.

The vertical delimitations are normally all defined 'floor to ceiling'. A station will have up to 8 coverage maps defined: ones for surveillance, lockout and datalink coverage of own station and potentially up to 5 lockout coverage maps for neighbouring stations operating together as a cluster (see later).

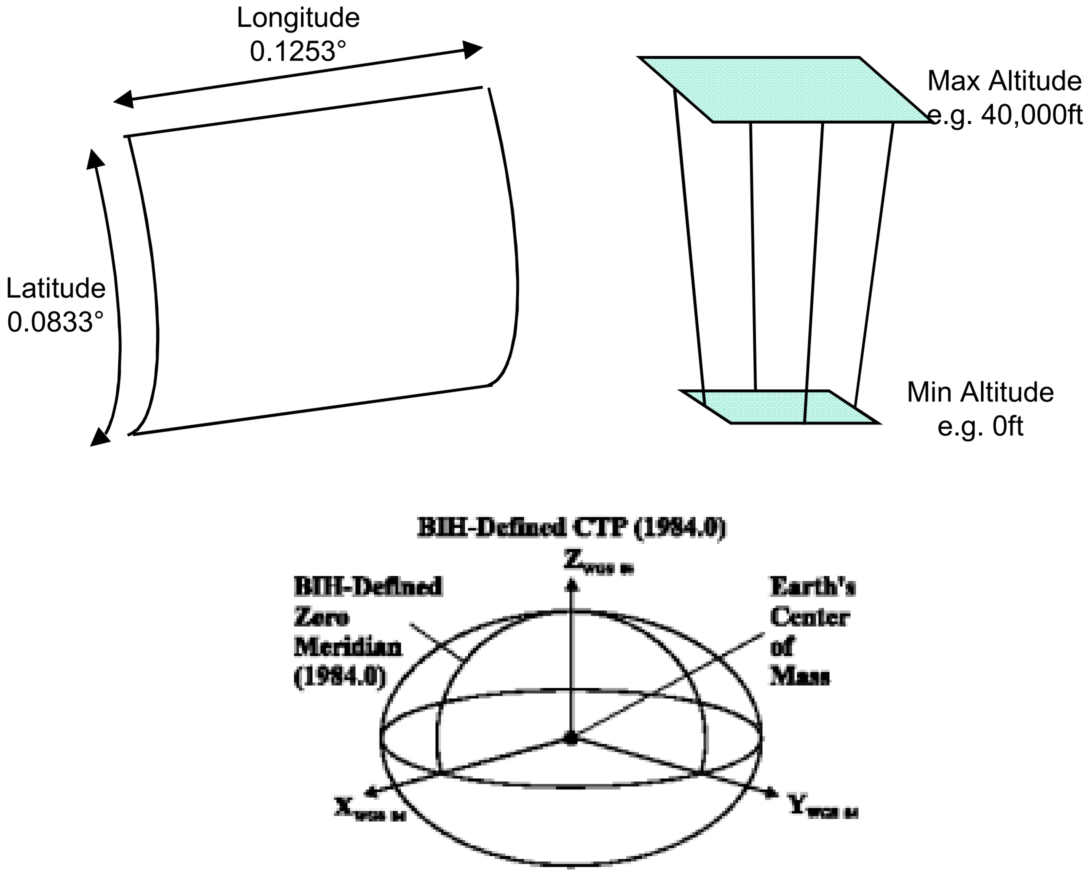

Figure 12 - EMS Coverage Cell

Figure 12 illustrates the horizontal and vertical components of a typical cell. The image also illustrates the WGS 84 principle. The Bureau International de l'Heure (BIH) defined the zero meridians, origin and axes of the WGS 84 co-ordinate system as follows:

Origin = Earth's centre of mass

Z-axis = The direction of the Conventional Terrestrial Pole (CTP) for polar motion, as defined by BIH on the basis of the co-ordinates adopted for the BIH stations.

X-axis = Intersection of the WGS 84 reference meridian plane and the plane of the CTP's equator, the reference meridian being the zero meridian defined by the BIH on the basis of the co-ordinates adopted for the BIH stations.

Y-axis = Completes a right-handed, Earth Centred, Earth Fixed (ECEF) orthogonal co-ordinate system, measured in the plane of the CTP equator, 90° East of the x-axis.

Co-ordinate transformations between those used locally at a sensor and the WGS 84 representation are defined in *[Ref. 6]* entitled "Co-ordinate Transformation Algorithms for the Hand-over of Targets between POEMS interrogators".

For each cell, the coverage map definition separately defines the responsibility of a sensor for surveillance, lockout and datalink as well as the coverage responsibilities of overlapping sensors operating together as a cluster.

6.2 Cell Allocation & Issues

From the perspective of IC allocation, the most important aspect of the responsibility maps is the lockout coverage map as derived for a particular IC. The allocation process foresees that optimisation of a sensors lockout coverage may be applied in order to maximise IC usage and system efficiency. However, optimising (refining) lockout coverage could have other effects on the RF environment and a careful strategy may be required to manage this.

Managing coverage responsibility within a sensor however is further complicated as the sensors allow for the interrogative range to vary by azimuth sector (e.g. sector of 1/32 of the 360º overall azimuth, giving approximately 11¼º per sector).

Internally, sensors generally use a range and azimuth based representation of their coverage. It is the responsibility of the sensor to perform the translation from the cell-based definition of the WGS 84 EMS coverage maps onto it's own internal system whilst maintaining the responsibility for targets in each of the cells.

An important factor also is that an interrogator's coverage is never exactly cylindrical. Various terrain effects will limit a sensor's lower coverage due to horizon and local obstacle terrain effects. Upper elevations of an SSR antenna leave an area of no coverage above the antenna which is know as the 'cone of silence' or also referred to as the 'overhead gap'.

Any initial implementation is likely to use static coverage maps, pre-programmed at the sensors. However, future stages of implementation may see certain pre-programmed states that could be used in the case of exceptions or even dynamic transmission of coverage maps from a remote maintenance site or control centre.

When a target is in the border area between two adjacent coverage cells, rules for operation are clearly defined in *[Ref. 4]*.

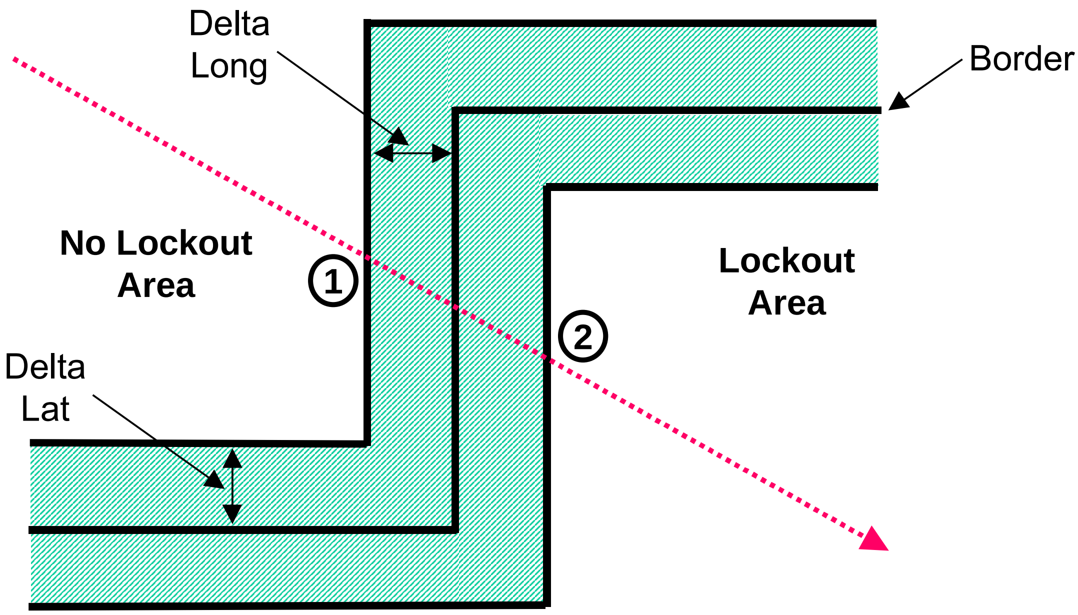

Figure 13. Responsibility Changes Between Cells

Figure 13 illustrates the border zone between a cell with lockout responsibility and an adjacent cell not having lockout responsibility. The coverage map specification defines the border zone to be specified by the station itself. It will depend on any errors in the transformation from the WGS 84 coverage map specification into the internal sensor map local reference system. This may have some errors due to sensors using map reference schemes which are determined on a range and azimuth basis rather than the coverage map basis. The size of the border zone should not be greater that 50% of cell size.

A track is shown where a target is crossing from a cell (zone) with no lockout responsibility into a zone with lockout responsibility. The decision on when to apply the change in responsibility for lockout is made by the station once the target has entered the border zone (i.e. between Point 1 and Point 2 as illustrated on the diagram).

6.3 Clusters

A cluster of sensors is a group of interrogators with overlapping coverage that have been networked together and are all using the same IC.

Just as for stand-alone interrogators with areas of overlapping coverage, there should be clear need for lockout and surveillance management between the interrogators in a cluster. Without a clear strategy, there is a risk of targets not being acquired by all interrogators in the cluster.

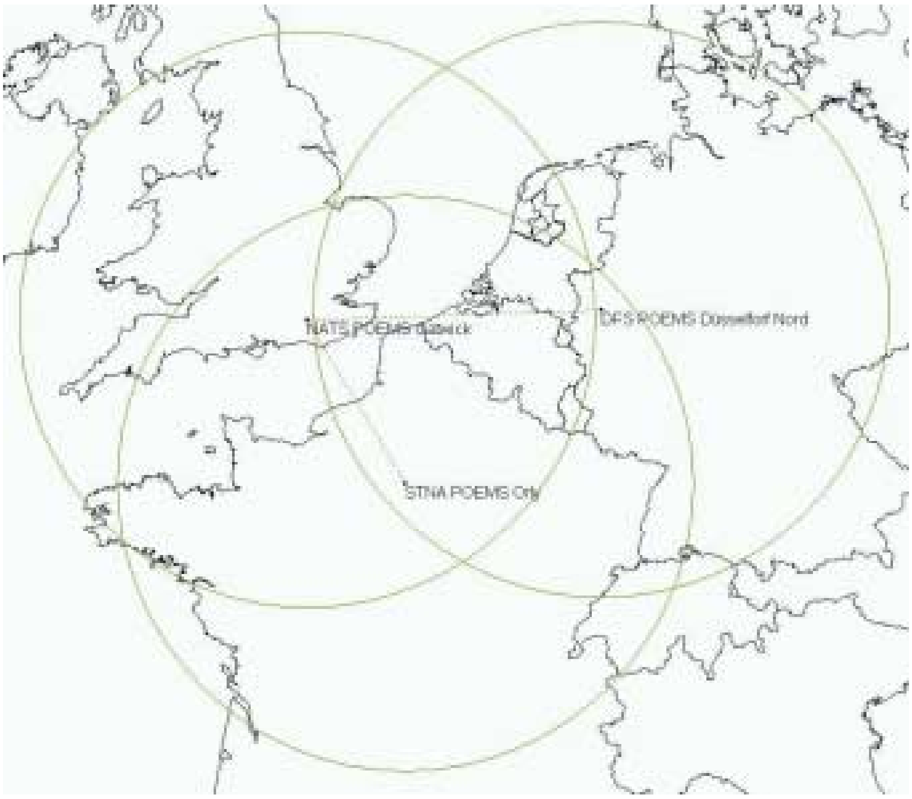

Figure 14 – An Example Cluster

From an IC allocation perspective, it is the responsibility of the ATSPs (Air Traffic Service Providers) operating these sensors to manage lockout, surveillance and datalink responsibilities within the cluster. Lockout responsibility will have been allocated for the cluster as a whole by the European Code Allocation Office (as if it were a single station).

Fortunately, there are clearly defined techniques to support this (Surveillance Co-ordination Function or SCF). Within the SCF is the Network Monitoring Protocol (NMP) which is a rule based protocol designed to support inter-sensor cluster co-ordination which can allow management to be distributed or centralised. Part of the NMP is the TASP which is the Track Acquisition and Support Protocol. This helps to provide track and acquisition information between sensors operating in a cluster.

The two distinct cluster management configurations possible are:

Centralised Control. This is the situation where one Cluster Controller (CC) manages all of the nodes in a cluster. The physical location of the CC need not necessarily be at one of the stations.

Distributed Control. Each station includes some limited cluster management functionality and applies a rule based approach to maintain effective cluster operation. In the case either there is no CC present or where connections with the CC are lost, the cluster nodes will switch to distributed control.

In any initial implementation, it is likely that distributed mode operation would be introduced first.

Configuration of the coverage responsibilities of sensors within a cluster is that of the authorities operating the sensors. Backup and fallback configurations may have to be defined as well as perhaps configurations to cover maintenance cycles.

It is expected that a networked (clustered) configuration will be required for the European scenario but that the initial implementation scenario will be standalone. Whilst alleviating IC availability issues, clustering adds complexity to the system design and ultimately, more cost. However, effective clustering could provide other operational benefits, especially an improved effect on FRUIT and interference levels on the RF frequencies (1030/1090 MHz).

In summary, there are several potential advantages of clustering such as several interrogators operating using a single IC (reducing the pressure on demands for ICs) and also for the potential reduction in all-call FRUIT (and hence system performance) if an effective (inter-) operating strategy were adopted. The main limitation of clustering is that it adds complexity (& hence cost) to the overall system design and requires additional management functionality for control and co-ordination.

6.4 Surveillance Co-ordination Function

The SCF is defined in detail in a specific ICD *[Ref. 4]*. EMS stations are designed to implement the SCF ICD and ASTERIX Category 017 *[Ref. 5]* is defined to support the encoding and transfer of these messages between all the nodes of the cluster. It is noted that the SCF defines one mechanism for cluster operation but that this is not a formal ICAO standard and other methodologies could also be used.

As stated, cluster operation can be centralised or it can also be distributed. Assuming centralised is the mode of choice, the operation of the cluster can be broken down into two distinct processes:

the Communications Process and

the Co-ordination Process

The communications process maintains the effective network topology, including the coverage map in use, the II/SI-Code of the stations and areas for lockout override to be applied. The NMP (or Network Monitoring Protocol) uses NIMs (or Network Information messages) to maintain cluster operation (a bit like ‘keep-alive’ message sent on a regular basis. In summary, the NMP takes care of network configuration, monitoring cluster stability, mode and state and also failure / exception management activities. This principle is illustrated in Figure 15 (assume that the two sensors shown are operating as a cluster).

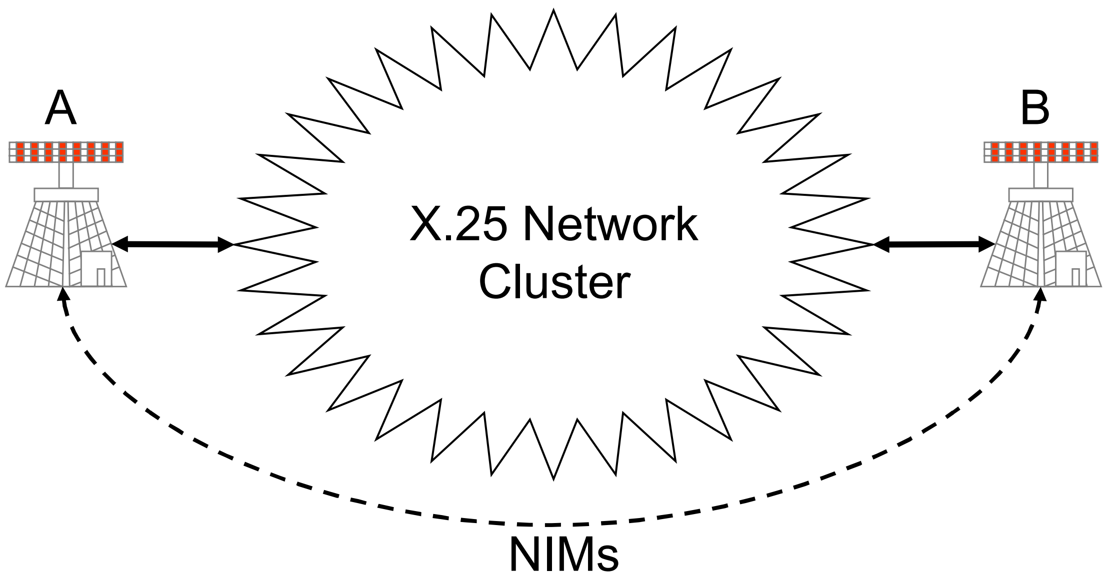

Figure 15. NMP

Sensors will have different states that they can go into depending on the status of the 'network'. For example:

State	Sensor A	Sensor B	Discussion
0	0	0	State not applicable
1	0	1	B standalone (as seen by B!)
2	1	0	A standalone (as seen by A!)
3	1	1	A+B networked (clustered)

Table 1. Network (Cluster) State Tables

In states 1 or 2, it is possible that intermittent lockout, along with supplementary acquisition techniques, might be used in areas where there is overlapping coverage between the two sensors. All possible states are fully defined in the Surveillance Co-Ordination Function ICD *[Ref. 4]*.

The co-ordination process uses the Target Acquisition and Support Protocol (or TASP). The TASP supports target hand-over between sites in a cluster as well as promulgating relevant known track information to other sites in the cluster. TASP comprises:

TAP = Target Acquisition Protocol and is used to provide track data between sensors in a cluster when a new track is arriving within coverage of the other interrogator.

TSP = Track Support Protocol and is used in the case where plots are 'missed' during one or more antenna revolutions (whilst a target is in 'allegedly' in coverage).

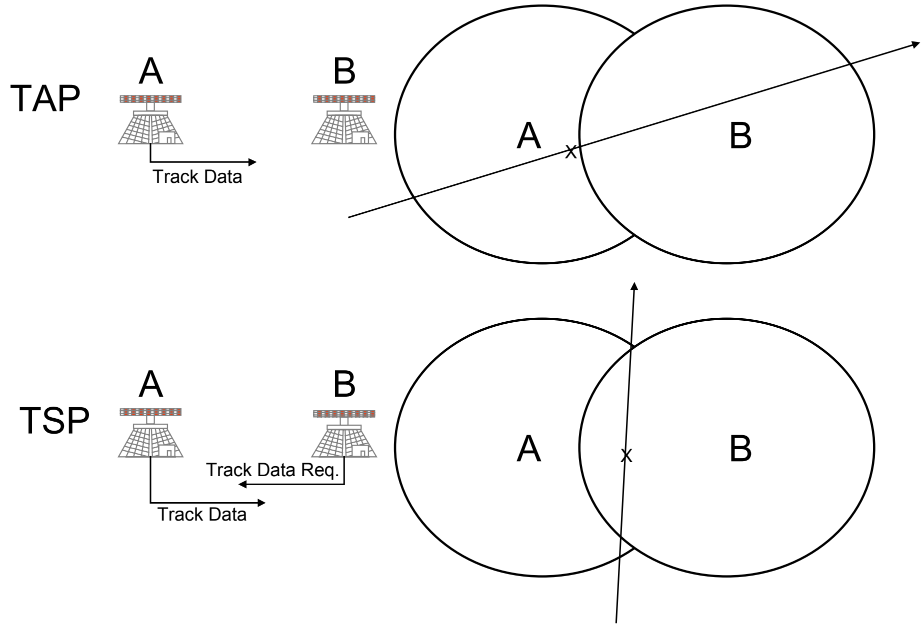

Figure 16. TASP

Figure 16 illustrates TAP and TSP operation, the X being to illustrate the point within coverage that the track data is exchanged. A complete set of state tables for the TASP are provided in *[Ref. 4]*. In addition to track initialisation, track update (as well as on 'miss') and cancellation / data stop states, there is also provision in the state tables to manage the scenario where duplicate addresses are detected.

The NNCOP (New Node & Change Over Protocol) is used during cluster reconfiguration or on sensor channel changeover. It is used to inform neighbour sensors of targets in areas of overlapping coverage (essentially, it is an exchange of a list of ICAO aircraft addresses between sensors).

Finally, the SCF documentation also defines both preventative and corrective mechanisms to manage the scenario where network overload occurs.

6.5 Coverage Map Definition

The detailed breakdown of the coverage map files is found in *[Ref. 3]*. This is a very detailed and formal definition of all fields that form part of a coverage map. Specifically of interest is the fact that the coverage map files contain information about adjacent coverage sensors of the same cluster. It also contains a detailed set of the 3 system maps (surveillance, lockout and datalink) for own sensor.

Coverage Map File

Cluster File
- Cluster Header Info
- Number of Nodes
- Node Descriptions (incl. II/Si-Code, Name, Reference, SIC/SAC, DTE Address, WGS84 position, etc)
- Cluster version numbers
- Modification History

System Map File
- Header Information
- Coverage Grid Definition
- Grid Origin (WGS 84)
- Coverage Grid (all the deltas for all of the cells)
- Cell Definitions
- Cell Content

Figure 17 – Coverage Map File

Figure 17 illustrates a high level view of the type of information that is held in a coverage map file.

7. SYSTEM OPTIMISATION

A fundamental operating principle is that the RF environment must be protected wherever possible, whilst at the same time ensuring that all targets in line of sight range have been acquired correctly and if they are in a cell where own sensor holds 'lockout responsibility', that these targets are consistently locked out as they pass through coverage until lockout responsibility ends.

It is normally the ATSP and it's regulatory authority that will are responsible for the management and for the lockout strategy within the bounds of the lockout coverage map that they have accepted from the EUROCONTROL code allocation office.

Three distinct stages could be foreseen to optimise system operation and reduce adverse RF environment effects.

Manual / Automated Conflict Resolution

Advanced Lockout and Override Strategies and

Clustering

Backup and fallback states are a serious issue to consider as well. In the case that a neighbouring clustered sensor or link to that clustered sensor fails, it may be possible to increase coverage of own interrogator in certain azimuth sectors and assume surveillance and / or lockout responsibility in other cells so that coverage loss in the overall system is minimised.

7.1 Manual / Automated Conflict Reduction

Taking the coverage maps of stations in conflict using the same IC and reducing the local surveillance and lockout coverage, the conflicts could be optimised and the conflicts resolved on a cell-by-cell basis.

This optimisation could be manual or semi-automated. There are tools available to compute and display the conflict cells and also to resolve them.

This is the simplest method of resolving conflicts but it becomes difficult to manage as the level of conflict / overlap increases.

Optimisation of coverage requirements for stations to suit the operational area and users to which they are supplying a service is another way to refine multi-station coverage. For example, country / FIR borders plus 30 NM is one possible way in which to optimise the coverage required for stations. When applying for ICs, the system operators are already requested to optimise their coverage requirement wherever possible.

7.2 Lockout Strategies

MIPs have been discussed in some detail earlier along with the principles of stochastic acquisition and lockout override. It is however possible, for systems, using the same IC in areas of overlapping coverage to adopt a strategy for ensuring detection and surveillance in these areas.

Multisite Lockout Override (MLO). Multisite lockout override is achieved using the SLA technique as described earlier – although the exact stochastic probabilities applied are not discussed here. The MLO must be applied in specific coverage areas (cellular) or by azimuth sector (i.e. for all targets from minimum to maximum range). This would depend on the strategy adopted. Application of MLO by azimuth sector has the advantage that (assuming stochastic probabilities are suitable) it can operate independently of any other adjacent sensors. However, the possibility for all-call garble and FRUIT are increased in some areas (See areas described in Figure 4).

Intermittent Lockout. The intermittent lockout technique can be applied simply to targets shown in the shaded area (See the shaded zone in Figure 5) by careful selection of the lockout zones defined in the coverage map. This mechanism may be more complex to define and initiate but it could improve the RF and detection situation. However, 'Intermittent Lockout' requires that all stations with coverage in the conflict area are 'playing the same game'. If they are, all of the stations should synchronise onto the intermittent lockout 'cycle'.

Zone of No Lockout. Having Azimuth sectors or coverage map ‘zones’ where lockout is not allowed. This has the potential disadvantage of generating unwanted all-call FRUIT and also requires that all stations in the conflict area are ‘playing the same game’.

7.3 Clustering

The principles of clustering and cluster operation have been addressed earlier in this document. The optimisation of the operation between adjacent stations in a cluster is the responsibility of the implementing authority. Careful management of the surveillance, lockout and datalink responsibilities between stations is required to ensure an effectively operating system.

The advantage of introducing clustering on the same IC is that strategies could be introduced to improve system operation and RF loading. The disadvantage however is that it could introduce significant complexity to the overall system design and hence cost.

Annex A - References

[Ref. 1] ICAO Annex 10 to the Convention on International Civil Aviation, Volumes III and IV, Amendment 77, 28th November 2002

[Ref. 2] Technical Approach for IC Allocation in Europe, V5, 12/11/01, Ref: MODE-S/SYSTEM/doc-01.

[Ref. 3] European Mode S Station Coverage Map Interface Control Document, Edition 1.13 (Released Issue), 19/04/2001, Ref: SUR/MODES/EMS/ICD-03. Available at: http://www.eurocontrol.int/mode_s/documentation/docs_intro.html

[Ref. 4] European Mode S Surveillance Co-ordination Interface Control Document, Edition 2.02 (Released Issue), 19/04/2001, Ref: SUR/MODES/EMS/ICD-01. Available at: http://www.eurocontrol.int/mode_s/documentation/docs_intro.html

[Ref. 5] POEMS Document for ASTERIX Category 017 – Transmission of Mode S Surveillance Co-ordination Function Messages, Edition 0.5 (Proposed Issue), February 2000, Ref: SUR.ET2.ST03.3111-SPC-02-00. Available at: http://www.eurocontrol.int/mode_s/documentation/docs_intro.html

[Ref. 6] Annex A to *[Ref. 5]*. Co-ordinate Transformation Algorithms for the Handover of Targets Between POEMS Interrogators. Available at: http://www.eurocontrol.int/mode_s/documentation/docs_intro.html

[Ref. 7] European Mode S Station Functional Specification. Available at: http://www.eurocontrol.int/mode_s/documentation/docs_intro.html. Edition 3.08, 19th April 2001, Ref: SUR/MODES/EMS/SPE-01.

Note: [Ref. 3] to [Ref. 7] are available for download from the EUROCONTROL web-site as shown.

Annex B - Abbreviations

ACAS	Airborne Collision Avoidance System
A-SMGCS	Advanced – Surface Movement and Guidance Control Systems
ASTERIX	All Purpose Structured EUROCONTROL Surveillance Information Exchange
ATC	Air Traffic Control
ATSP	Air Traffic Service Provider
BIH	Bureau International de l'Heure
CC	Cluster Controller
CTP	Conventional Terrestrial Pole
DTE	Data Terminal Equipment
EATMP	European Air Traffic Management Programme
ECEF	Earth Centre, Earth Fixed
EHS	Enhanced Surveillance
ELE	Elementary Surveillance
ELS	Elementary Surveillance
EMS	European Mode S (ground station)
IC	Interrogator Code
ICAO	International Civil Aviation Organisation
ICD	Interface Control Document
II-Code	Interrogator Identifier Code
MHz	Megahertz
MIP	Mode Interlace Pattern
MLO	Multisite Lockout Override
Mode A/C	Mode Alpha / Charlie
Mode S	Mode Select
NIM	Network Information Message

NM	Nautical Miles
NMP	Network Monitoring Protocol
NNCOP	New Node & Change Over Protocol
NP-Complete	Nondeterministic Polynomial – Complete
POEMS	Pre-Operational European Mode S Station
PR	Probability of Reply
RC	Roll Call (period)
RF	Radio Frequency
SAC	System Area Code
SCF	Surveillance Co-ordination Function
SI-Code	Surveillance Identifier Code
SIC	System Identification Code
SLA	Stochastic Lockout (override) Acquisition
SSR	Secondary Surveillance Radar
STCA	Short Term Conflict Alert
TAP	Target Acquisition Protocol
TSP	Track Support Protocol
TASP	Target Acquisition and Support Protocol
UK	United Kingdom
WGS (84)	World Geodetic System (84)