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Subject:	Compliance Verification for Mode S Transponder Elementary Surveillance (ELS), Enhanced Surveillance (EHS), and Automatic Dependent Surveillance via Broadcast (ADS-B) Applications
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PREFACE

This project memorandum is the result of research and development sponsored by the United States Air Force (USAF) Global Air Traffic Systems Group of the Electronic Systems Center at Hanscom Air Force Base, MA. The authors have prepared this report to assist the USAF in the task of equipping their aircraft with appropriate Mode S avionics to support the European mandate for "Elementary Surveillance" (ELS) and "Enhanced Surveillance" (EHS) applications.

The authors acknowledge the many writers and reviewers who prepared references [2] through [8], from which this project memorandum derives much of its material. The authors would like to thank the reviewers who provided many significant comments and corrections on earlier drafts of this project memorandum.

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EXECUTIVE SUMMARY

The European mandate for Mode S "Elementary Surveillance" (ELS) and "Enhanced Surveillance" (EHS) equipage raises a requirement to generate appropriate conformance testing procedures for the new avionics. The increasing interest in the use of Mode S 1090 MHz Extended Squitter ADS-B in the support of air-traffic control applications (e.g., in Australia, Indonesia, and the U.S.) will also require a means to test Mode S avionics for a whole new range of functionality.

This project memorandum provides guidance for implementers and testers of avionics installations supporting the Mode S "Ground-Initiated Comm. B" (GICB) transponder protocols. A comprehensive set of conformance tests for the ELS, EHS, and ADS-B applications is described. The test procedures described in this project memorandum go beyond the standard "bench tests" typically employed for Mode S transponders to provide a means to verify proper operation of the total end-to-end avionics system supporting the specific Mode S applications. These conformance test procedures not only check that the application data is properly formatted but also actually measure the accuracy of application data by comparison with independently measured surveillance from a ground radar sensor.

The typical set of Mode S conformance tests (such as those defined by the "European Organization for Civil Aviation Equipment" (EUROCAE) in Working Group 49) treat only the transponder. It is assumed that known data can be provided to the transponder via one or more ARINC 429 interfaces. The test procedure then verifies that the contents of the Mode S GICB registers in the transponder are correctly set. Each required data item in each Mode S GICB register required for the ELS, EHS, and ADS-B applications is tested in turn. These tests validate that the Mode S transponder has properly reformatted the data input from its interfaces, but there are no requirements on the accuracy of some of the data provided on those interfaces, and no testable requirements for the accuracy of the data actually reported by the transponder. The conformance tests described in this project memorandum incorporate both format and data accuracy validation procedures. The data accuracy tests are derived from the operational performance capabilities of existing ground radar surveillance systems.

The use of specified "bench tests" to define conformance to the European ELS and EHS mandate will cause problems for the military. Unlike commercial aircraft, military aircraft may not have ARINC 429 interfaces to their Mode S transponder. There may be special military transponder interfaces, or there may be separate equipment acting as a "data concentrator" between some avionics systems and the transponder itself. Military aircraft may have special flight control avionics rather than typical commercial flight management systems where data required for Mode S transponder testing is not readily available. The degree of available data accuracy for given data items in military avionics systems may not parallel those of the specific ARINC 429 data words defined in the bench tests. Different sets of conformance tests for each

type of military aircraft configuration may be required – an onerous and expensive task. This task will become even more difficult when the complexity of the ADS-B application is included.

The testing of the Mode S transponder separately from the rest of the avionics might miss potential fault conditions in the overall system. A full, end-to-end, test of the entire Mode S avionics suite in a manner equivalent to the way the avionics will actually support the desired Mode S applications is the most complete and accurate way to fully evaluate the system.

This project memorandum describes such a set of end-to-end conformance tests for the Mode S avionics in an aircraft supporting the ELS, EHS, and ADS-B applications. These conformance tests do not require any invasive connections to the aircraft equipment. It is assumed that the aircraft under test will fly in the coverage of a ground radar surveillance sensor whose surveillance data is available to the test system. It is also assumed that the test system can direct the ground sensor (either a Mode S surveillance radar or an independent Mode S sensor) to extract specific GICB registers from the aircraft's Mode S transponder and can receive the register contents. (Note: the conformance testing can either be done in real time or done off-line if sufficient ground recording with accurate time-tagging of the Mode S sensor data is available.) The conformance tests described in this project memorandum parallel the way that the actual ELS, EHS, and ADS-B applications will operate.

This project memorandum also includes a description of how the obtainable accuracy for the Mode S ELS, EHS, and ADS-B data may be derived from the surveillance accuracy available from a Mode S ground sensor. The application accuracy requirements should be based on achievable system performance. It is one thing to simply require that data in an ARINC 429 word be loaded into a specific Mode S transponder register, but it is quite a different thing to determine how a military aircraft flying in European airspace might be flagged for non-conformance to the required equipage mandates. Passing the Mode S conformance tests described in this project memorandum goes a long way towards assuring that an aircraft's avionics will work properly with the Mode S applications anywhere in the world.

1 Introduction

This project memorandum itemizes the required steps for compliance verification to be performed on Mode S avionics supporting the "elementary surveillance" (ELS) and "enhanced surveillance" (EHS) data link applications. The basis for this project memorandum is reference [1], "Guidance Material for Mode S-Specific Protocol Application Avionics" , which resolves the complexity in several other Mode S specifications (references [2] through [7]). Refer to those documents for detailed specifications of Mode S transponder performance.

In addition to compliance tests to confirm the Mode S performance required by the European ELS and EHS mandates, this paper extends the compliance verification to include the Mode S Automatic Dependent Surveillance via Broadcast (ADS-B, also known as "1090 MHz Extended Squitter") application. The Mode S ADS-B application is not a part of the Eurocontrol mandate, nor does it require full ELS or EHS support as a prerequisite. However, the Federal Aviation Administration (FAA) has shown movement toward increasing use of ADS-B and a possible mandate for ADS-B equipage in the National Airspace System (NAS).

Although the information provided in this Project Memorandum is drawn from several approved national and international standards, it is not intended to replace or supercede those standards. Rather, this report is meant to provide guidance for system implementers and testers. In the event of a conflict or contradiction between this document and any approved standards, the approved standards take precedence and the reader is encouraged to contact the author of this report.

The tests described herein form the basis for the determination of whether the avionics in a specific aircraft comply with the upcoming Eurocontrol mandate for Mode S ELS and EHS equipage[1]. The processes described in this paper determine whether the avionics and transponder registers are properly interconnected and populated. Further, the data-correctness tests verify that the data values are accurate and timely. Sections 2 through 4 of this project memorandum describe the compliance tests, while section 5 describes the data validation tests. In other words, the testing procedures for the Mode S applications might take the following four levels, to determine whether the:

- necessary status bit(s) that indicate whether the registers are being filled;
- data field status bit(s) in each required register are set;
- data fields in each required register have non-zero values; and
- data field values are compatible with independently derived data.

This project memorandum assumes that each Mode S transponder register holds 56 bits of data (seven bytes). The bits in each register are numbered from 1 to 56 – bit 1 being the high-order bit of the first byte in the register data. Bit 56 is the low-order bit of the seventh byte

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[1] See "http://www.eurocontrol.int/msa/public/subsite_homepage/homepage.html"

in the register data. Each register number is given as a hexadecimal value, denoted with a subscript "$_{16}$".

It should be noted that each test described herein builds on the preceding tests. ELS support (section 2) is required for EHS support (section 3). The tests within each major section are ordered such that all previous tests must be passed first – i.e., the tests should be performed in the order given in this project memorandum. The compliance tests for ADS-B support are given in section 4. Data validation tests for each of the applications (ELS, EHS, and ADS-B) are given in section 5.

In some cases, a test failure is so fundamental that there is no value in continuing to extract or examine register contents (e.g., CA<4, see section 2.2 below). In such cases, the resulting non-compliance report may not indicate all transponder problems. However, some test failures do not preclude additional tests. When possible, the Mode S compliance verification process will continue even after a test has failed. In any event, a non-compliance report will indicate all detectable test failures.

The compliance text in the following sections includes many "Error condition:" indications in bold, red text. Those indicate the errors that have been detected and indicate the text messages to be generated by the Mode S compliance verification system. An alert of non-compliance will contain one or more of these statements, one for each detectable failure. Section 6 of this project memorandum describes the output format for the non-compliance reports.

The following figure illustrates the organization and basic data flows for the subset of the registers used in the ELS, EHS, ADS-B, and military applications.

Figure 1-1: Mode S Register Assignments for ELS, EHS, and ADS-B

This figure illustrates the organization and basic data flows for the subset of the registers used in the ELS, EHS, ADS-B, and military applications. Color-coding is used to group the registers by application: ELS (yellow), EHS (red), ADS-B (blue), and military (green). Registers shown in gray are indirectly involved with these applications, but are not directly called out by the application specification. The figure employs thick arrows to denote the transponder static and dynamic configuration data flows and the ADS-B event-driven protocol.

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2 Elementary Surveillance (ELS)

The tests for ELS compliance deal with the basic Mode S transponder data communication capability and with the four Mode S transponder registers:

Table 2-1: ELS Transponder Registers

Register Number	Contents
10_{16}	Data link capability report
17_{16}	Common usage GICB capability report
20_{16}	Aircraft identification
30_{16}	ACAS active resolution advisory

Some other registers and transponder data fields are involved as part of the configuration of the transponder.

2.1 Basic Transponder Tests

In order to support the ELS application, the Mode S transponder must provide the following in its surveillance replies:

a) A valid Mode S 24-bit address (not all zeroes, all ones, or just a country code). The bit pattern of the address must agree with the coding definition for the specific state (e.g., the U.S. employs an algorithm that maps the aircraft tail number to the Mode S address).

Error condition:	**Transponder does not respond with a valid Mode S Address**

b) Response to Mode S interrogations for Mode 3/A identity code; and

Error condition:	**Transponder does not respond to Mode 3/A identity code interrogations**

c) Response to Mode S interrogations for Mode C altitude.

Error condition:	**Transponder does not respond to Mode C altitude interrogations**

2.2 Transponder CA Field

The 3-bit transponder capability (CA) field is obtained from either the aircraft's "Mode S All-Call Reply and Acquisition Squitter" (DF=11) or the "Extended Squitter" (DF=17) downlink messages. To support ELS, the CA field value must be greater than 3.

Error condition:	**Transponder capability (CA) is less than 3; does not support Mode S data link applications**

2.3 Capability Report Registers

Bits in the Mode S Specific-Services GICB Capability registers indicate whether the avionics are configured to support individual transponder registers. Register 18_{16} contains bits for the configuration status of registers 01_{16} through 38_{16}, which includes all those involved with ELS. The register configuration bits are assigned sequentially starting with the low-order bit in the register (bit 56). These bits represent the wired configuration of the avionics – they are static and need to be extracted only once. To support ELS, the following bits in register 18_{16} must be set to 1:

a) Bit 41 (refers to register 10_{16});

Error condition:	**Bit 41 of register 18_{16} (Static Configuration) is not set to 1 implies that ELS register 10_{16} is not available. Transponder does not support ELS**

b) Bit 34 (refers to register 17_{16});

Error condition:	**Bit 34 of register 18_{16} (Static Configuration) is not set to 1 implies that ELS register 17_{16} is not available. Transponder does not support ELS**

c) Bit 25 (refers to register 20_{16}); and

Error condition:	**Bit 25 of register 18_{16} (Static Configuration) is not set to 1 implies that ELS register 20_{16} not available. Transponder does not support ELS Bit 9 (refers to register 30_{16}).**
Error condition:	**Bit 9 of register 18_{16} (Static Configuration) is not set to 1, implies that ELS register 30_{16} is not available. Transponder does not support ELS**

A transponder anomaly report could indicate one or more of the preceding four error conditions.

2.4 Common Usage Capability Register

The Mode S "common-usage" transponder capability register (17_{16}) contains configuration bits that are set to indicate the actual operational status (dynamic) of the most commonly used registers (including all ELS registers). To support ELS, bit 7 (corresponding to register 20_{16}) in register 17_{16} must be set to 1.

Error condition:	**Bit 7 of register 17_{16} (Dynamic Configuration) is not set to 1 implies that ELS register 20_{16} is not currently available. Transponder does not support ELS.**

2.5 Data Link Capability Register

The Mode S transponder data link capability register (10_{16}) contains a number of avionics configuration and status fields. To support ELS, the following must all be true:

a) Bits 1 through 8 (BDS code) = 10_{16};

Error condition:	The value in bits 1-8 of ELS register 10_{16} is not set to 10_{16}; incorrect register identifier (BDS code).

b) Bits 17 through 23 (subnetwork version number) must be in the range 0..4;

Error condition:	The value in bits 17-23 (version number) of ELS register 10_{16} is not in range 0..4. Incorrect sub-network version number, transponder does not support ELS.

c) Bit 25 (Mode S Specific-Services Capability) = 1; and

Error condition:	Bit 25 of ELS register 10_{16} (Mode S Specific-Services Capability) is not set to 1; transponder does not support ELS.

d) Bit 33 (Aircraft Identification Capability) = 1.

Error condition:	Bit 33 of ELS register 10_{16} (Aircraft identification capability) is not set to 1; transponder does not support ELS.

2.6 Aircraft Identification Register

Mode S transponder register 20_{16} supports the aircraft identification function for ELS. Bits 1 through 8 of the register must hold the BDS code value 20_{16}.

Error condition:	The value in bits 1-8 of ELS register 20_{16} is not set to 20_{16}; incorrect register identification (BDS code)

The remaining 48 bits of the register form a string of eight characters. Character 1 is in bits 9 through 14, while character 8 is in bits 51 through 56. The character encoding value must obey the following rules:

Table 2-2: Value Ranges for Flight Identification

Values	Character Type
1-26	(letters)
32	(space)
48-57	(digits)

No other character values (0, 27..31, 33..47, and 58..63) are legal in the register. The character string must be left justified with no intervening spaces (encoding 32). Any unused characters at the end of the string should be set to spaces (encoding 32).

Error condition: **Invalid flight identification encoding in ELS register 20_{16}. Invalid values in the aircraft identification character string.**

2.7 ACAS Advisory Register

Mode S transponder register 30_{16} is used to report resolution advisory data from an onboard TCAS unit. For ELS compliance, bits 1 through 8 (BDS code) must contain the value 30_{16}.

Error condition: **The value in bits 1-8 of ELS register 30_{16} is not set to 30_{16}; incorrect register identifier (BDS code).**

2.8 Transponder Fully ELS-Compliant

If the transponder does not fail any of the preceding tests, then it is deemed fully compliant with the ELS mandate and no error report based on ELS non-compliance is generated. However, the transponder is not deemed compliant with the European Mode S mandate unless it also passes all of the following EHS compliance verification tests as well.

3 Enhanced Surveillance (EHS)

EHS support requires all of the ELS support (section 2 above) plus support for Mode S transponder registers 40_{16}, 50_{16}, and 60_{16}. The support of EHS also touches some of the configuration registers previously described in section 2.

Table 3-1: EHS Transponder Registers

Register Number	Contents
40_{16}	Selected Vertical Intent Report
50_{16}	Track and Turn Report
60_{16}	Heading and Speed Report

3.1 Capability Report Registers

The configuration bits for the EHS registers are found in register 19_{16}. To support EHS, the following bits in register 19_{16} must be set to 1:

a) Bit 48 (refers to register 40_{16})

Error condition:	**Bit 48 of register 19_{16} (Static Configuration) is not set to 1 implies that EHS register 40_{16} not available. Transponder does not support EHS.**

b) Bit 33 (refers to register 50_{16})

Error condition:	**Bit 33 of register 19_{16} (Static Configuration) is not set to 1 implies that EHS register 50_{16} not available. Transponder does not support EHS.**

c) Bit 17 (refers to register 60_{16})

Error condition:	**Bit 17 of register 19_{16} (Static Configuration) not set to 1 implies that EHS register 60_{16} not available. Transponder does not support EHS.**

3.2 Common Usage Capability Register

The following additional configuration bits must be set to 1 in the common-usage capability register (17_{16}) to support EHS (in addition to bit 7 required for ELS):

a) Bit 9 (refers to register 40_{16})

Error condition:	**Bit 9 of register 17_{16} (Dynamic Configuration) not set to 1 implies that EHS register 40_{16} not currently available. Transponder does not support EHS.**

b) Bit 16 (refers to register 50_{16})

Error condition:	**Bit 16 of register 17_{16} (Dynamic Configuration) not set to 1 implies that EHS register 50_{16} not currently available. Transponder does not support EHS.**

c) Bit 24 (refers to register 60_{16})

Error condition:	**Bit 24 of register 17_{16} (Dynamic Configuration) not set to 1 implies that EHS register 60_{16} not currently available. Transponder does not support EHS.**

3.3 Selected Vertical Intent Register

The Mode S selected vertical intention transponder register (40_{16}) contains five binary data fields. Each field starts with a status bit indicating whether that data field is valid. At least one of the status bits (bit 1, 14, 27, 48, or 54) must be set to 1 for EHS support.

Error condition:	**All data field status bits in EHS register 40_{16} cleared to 0. No valid data in the register. Transponder does not support EHS.**

Bits 40 through 47 and 52 through 53 are reserved and should be cleared to zero.

Error condition:	**Reserved bits in EHS register 40_{16} are not cleared to zero; invalid register contents.**

If the status bit for a data field is zero (indicating that there is no current data for that field), then the data bits for the field should be cleared to all zeroes.

Error condition:	**Status bit(s) cleared to 0, but corresponding data fields not cleared to 0 in EHS register 40_{16}; invalid register contents.**

3.4 Track and Turn Report

The Mode S track and turn transponder register (50_{16}) contains five binary data fields. Each field starts with a status bit indicating whether that data field is valid. At least one of the status bits (bit 1, 12, 24, 35, or 46) must be set to 1 for EHS support.

Error condition:	**All data field status bits in EHS register 50_{16} cleared to 0. No valid data in the register. Transponder does not support EHS.**

If the status bit for a data field is zero (indicating that there is no current data for that field), then the data bits for the field should be cleared to all zeroes.

Error condition:	**Status bit(s) cleared to 0, but corresponding data fields not cleared to 0 in EHS register 50_{16}; invalid register contents.**

3.5 Heading and Speed Report

The Mode S heading and speed transponder register (60_{16}) contains five binary data fields. Each field starts with a status bit indicating whether that data field is valid. At least one of the status bits (bit 1, 13, 24, 35, or 46) must be set to 1 for EHS support.

Error condition:	**All data field status bits in EHS register 60_{16} cleared to 0. No valid data in the register. Transponder does not support EHS.**

If the status bit for a data field is zero (indicating that there is no current data for that field), then the data bits for the field should be cleared to all zeroes.

Error condition:	**Status bit(s) cleared to 0, but corresponding data fields not cleared to 0 in EHS register 60_{16}; invalid register contents**

4 Mode S ADS-B (1090 MHz Extended Squitter)

This section of this project memorandum will describe the compliance testing required for a set of Mode S avionics to support the ADS-B (1090 MHz Extended Squitter) application. It should be noted that, as was the case for the ELS and EHS applications, the compliance tests described in this section of the paper only indicate that the avionics and transponder registers are properly interconnected and populated – they do not check that the data values placed in the Mode S transponder registers are actually correct with respect to the aircraft's state of flight. Further data validation tests (such as those described in section 5) would be required to verify that the data values are accurate and updated in a timely fashion.

Note: there are currently two valid definitions for the Mode S ADS-B register format. The earlier format specification is denoted "Version 0" [6], while the revised specification is denoted "Version 1" [7]. The ADS-B compliance tests described in this project memorandum will apply to both ADS-B specification versions except where explicitly noted.

4.1 Basic Transponder Tests for Mode S ADS-B

To support Mode S ADS-B, the aircraft avionics must include a functioning Mode S transponder with a valid 24-bit address (not all zeroes, all ones, or just a country code). The bit pattern of the address must agree with the coding definition for the specific state (e.g., the U.S. employs an algorithm that maps the aircraft tail number to the Mode S address).

Error condition:	**Transponder does not reply with a valid Mode S address**

4.2 Transponder CA Field for Mode S ADS-B

The 3-bit transponder capability (CA) field is obtained from either the aircraft's "Mode S All-Call Reply and Acquisition Squitter" (DF=11) or the "Extended Squitter" (DF=17) downlink messages. To indicate support for Mode S ADS-B, the CA field value must be greater than 3.

Error condition:	**Transponder capability (CA) value is less than 3; does not support Mode S data link applications**

4.3 Capability Report Registers for Mode S ADS-B

Bits in the Mode S Specific-Services GICB Capability registers indicate whether the avionics are configured to support individual transponder registers. Mode S specific-services GICB capability register 18_{16} contains a set of bits for the static configuration status of registers 01_{16} through 38_{16} (all those involved with ELS). The register configuration bits are assigned sequentially starting with the low-order bit in the register (bit 56). These bits represent the wired configuration of the avionics – they are static and need to be extracted only once. To indicate full support for Mode S ADS-B, the following bits in Mode S specific-services GICB capability report register 18_{16} must be set to 1:

a) Bit 52 (refers to register 05_{16})

Error condition:	**Bit 52 of register 18_{16} (Static Configuration) is not set to 1, implies that ADS-B register 05_{16} is not available. Transponder does not support ADS-B.**

b) Bit 51 (refers to register 06_{16})

Error condition:	**Bit 51 of register 18_{16} (Static Configuration) is not set to 1, implies that ADS-B register 06_{16} is not available. Transponder does not support ADS-B.**

c) Bit 50 (refers to register 07_{16})

Error condition:	**Bit 50 of register 18_{16} (Static Configuration) is not set to 1, implies that ADS-B register 07_{16} is not available. Transponder does not support ADS-B.**

d) Bit 49 (refers to register 08_{16})

Error condition:	**Bit 49 of register 18_{16} (Static Configuration) is not set to 1, implies that ADS-B register 08_{16} is not available. Transponder does not support ADS-B.**

e) Bit 48 (refers to register 09_{16})

Error condition:	**Bit 48 of register 18_{16} (Static Configuration) is not set to 1, implies that ADS-B register 09_{16} is not available. Transponder does not support ADS-B.**

f) Bit 47 (refers to register $0A_{16}$)

Error condition:	**Bit 47 of register 18_{16} (Static Configuration) is not set to 1, implies that ADS-B register $0A_{16}$ is not available. Transponder does not support ADS-B.**

4.4 Common Usage Capability Register for Mode S ADS-B

The Mode S "common-usage" transponder capability register (17_{16}) contains a set of configuration bits that are set to indicate the actual operational status (dynamic) of the registers most commonly used for currently-defined Mode S data link applications (including all Mode S ADS-B registers). To indicate full support for Mode S ADS-B, the following bits in register 17_{16} must be set to 1:

a) Bit 1 (refers to register 05_{16})

Error condition:	**Bit 1 of register 17_{16} (Dynamic Configuration) is not set to 1, implies that ADS-B register 05_{16} is not currently available. Transponder does not support ADS-B.**

b) Bit 2 (refers to register 06_{16})

Error condition:	**Bit 2 of register 17_{16} (Dynamic Configuration) is not set to 1, implies that ADS-B register 06_{16} is not currently available. Transponder does not support ADS-B.**

c) Bit 3 (refers to register 07_{16})

Error condition:	**Bit 3 of register 17_{16} (Dynamic Configuration) is not set to 1, implies that ADS-B register 07_{16} is not currently available. Transponder does not support ADS-B.**

d) Bit 4 (refers to register 08_{16})

Error condition:	**Bit 4 of register 1 7_{16} (Dynamic Configuration) is not set to 1, implies that ADS-B register 08_{16} is not currently available. Transponder does not support ADS-B.**

e) Bit 5 (refers to register 09_{16})

Error condition:	**Bit 5 of register 17_{16} (Dynamic Configuration) is not set to 1, implies that ADS-B register 09_{16} is not currently available. Transponder does not support ADS-B.**

f) Bit 6 (refers to register $0A_{16}$)

Error condition:	**Bit 6 of register 17_{16} (Dynamic Configuration) is not set to 1, implies that ADS-B register $0A_{16}$ is not currently available. Transponder does not support ADS-B.**

4.5 Data Link Capability Register for Mode S ADS-B

The Mode S transponder data link capability register (10_{16}) contains a number of avionics configuration and status fields. To support Mode S ADS-B, the following must be true:

a) Bits 1 through 8 (BDS code) = 10_{16}

Error condition:	**Bits 1-8 of register 10_{16} not set to 10_{16}; incorrect register identification.**

b) Bits 17 through 23 (sub-network version number) must be in the range 0..4

Error condition:	**The value in bits 17-23, register 10_{16} do not lie in range 0..4; not a defined ADS-B version number. Transponder does not support ADS-B.**

c) Bit 25 (Mode S Specific-Services Capability) = 1

Error condition:	**Bit 2 of register 10_{16} (Mode S specific-Services Capability) is not set to 1. Transponder does not support ADS-B.**

d) Bit 34 (Mode S Extended Squitter registers 05_{16} and 06_{16} loaded) = 1

Error condition:	**Bit 34 of register 10_{16} (Mode S Extended Squitter register loaded) is not set to 1. Transponder does not support ADS-B.**

4.6 Extended Squitter Airborne Position (Register 05_{16})

The first 5 bits in this register constitute a format type-code value. If this value is zero, then the avionics are not supplying current navigational information and no Mode S ADS-B processing can be done. Valid values for the format type-code indicating airborne position range from 9 through 22.

Error condition:	**The value in bits 1..5 of ADS-B register 05_{16} (format type-code for airborne position) lies outside the range of 9 through 22; value is not valid. Transponder does not support ADS-B.**

4.7 Extended Squitter Surface Position (Register 06_{16})

The first 5 bits in this register constitute a format type-code value. If this value is zero, then the avionics are not supplying current navigational information and no Mode S ADS-B processing can be done. Valid values for the format type-code indicating surface position range from 5 through 8.

Error condition:	**The value in bits 1..5 of ADS-B register 06_{16} (format type-code for surface position) lies outside the range of 5 through 8; value is not valid. Transponder does not support ADS-B.**

4.8 Extended Squitter Status (Register 07_{16})

There are no Mode S ADS-B compliance tests for this register.

4.9 Extended Squitter Aircraft Identification (Register 08_{16})

The first 5 bits in this register constitute a format type-code value. If this value is zero, then the avionics are not supplying current navigational information and no Mode S ADS-B processing can be done. Valid values for the 1090 MHz Extended Squitter format type-code indicating aircraft identification range from 1 through 4.

Error condition:	**The value in bits 1..5 of ADS-B register 08_{16} (format type-code for aircraft identification) lies outside the range of 1 through 4; value is not valid. Transponder does not support ADS-B.**

The category of vehicle transmitting the Mode S Extended Squitters is encoded in the format type-code in the following table:

Table 4-1: Vehicle Type Codes and Definitions

Type-code Value	Vehicle Type
1	Reserved
2	Ground vehicle or fixed transmitter
3	Special aircraft (glider, UAV, spacecraft, balloon, etc.)
4	Normal aircraft

Bits 6 through 8 in the register define a sub-type encoding that subdivides each vehicle type further. The value 7 (all ones) is reserved and should not be used.

Error condition: Value in bits 6..8 of ADS-B register 08_{16} (sub-type coding for vehicle) is not valid. Transponder does not support ADS-B.

The remaining 48 bits of the register (bits 9 through 56) contain a character string identifying the squittering vehicle. The rules for the formation of the character string are identical to those for "aircraft identification register" as part of the ELS application (see section 2.6 Table 2-1 above).

Error condition: Invalid character string encoding in ADS-B register 08_{16}. The vehicle identification is incorrectly formatted.

4.10 Extended Squitter Airborne Velocity (Register 09_{16})

The first 5 bits in this register constitute a format type-code value that must be set to the value 19 for airborne velocity.

Error condition: The value in bits 1..5 of ADS-B register 09_{16} (format type-code for airborne velocity) is not set to 19. Transponder does not support ADS-B.

The next 3 bits constitute a sub-type code that must lie in the range 1 through 4.

Error condition: The value in bits 6..8 of ADS-B register 09_{16} (sub-type coding for airborne velocity) is not valid. Transponder does not support ADS-B

Bits 11 through 13 contain the "navigational uncertainty category" (NUC) for velocity in the Version 0 specification – they contain the "navigational accuracy category" (NAC) for velocity in the Version 1 specification. Valid values for NUC (or NAC) range between 0 and 4.

Error condition: The value in bits 11..13 of ADS-B register 09_{16} (NUC or NAC for airborne velocity) is not valid. Transponder does not support ADS-B

4.11 Extended Squitter Event-Driven Information (Register $0A_{16}$)

There are no Mode S ADS-B compliance tests for this register. This register is not normally extracted by external applications. The avionics would actually load one or more of the event-driven register set (61_{16}-65_{16}). The contents of these registers would be cycled through ADS-B register $0A_{16}$ as required by the ADS-B event-driven protocol for output as special occasion squitters.

5 Data Validation

The previous sections of this project memorandum deal with proper status settings and data extraction. This section deals with the validation of data received from the registers; that is, the examination of the extracted data to ensure that it is consistent with the physical state of the aircraft. In general, the validation tests described below require the results of a target tracker and flight plan data feed that provide independent sources of aircraft flight, pilot intent, and aircraft state data.

5.1 ELS Data Validation

If the ELS compliance tests described in section 2 have been successfully passed, then the following data validation tests are to be performed using available external sources of data, such as the aircraft's flight plan.

Note: data validation for the ACAS Active Resolution Advisory (register 30_{16}) component of ELS would be performed using a special bench or ramp tester that can generate the appropriate Mode S signals. (It would be very difficult to produce reliable ACAS RA's via a flight test program.)

5.1.1 Flight Status

The 3-bit flight status (FS) field is contained in each Mode S surveillance reply. Flight Status includes three types of information:

(a) Indication of whether the aircraft is airborne or on the ground;

(b) Presence of a Mode 3/A code "alert" condition; and

(c) The "special position indicator" (SPI).

A Mode 3/A "alert" condition indicates that the aircraft's Mode 3/A code has changed since the last time it was read out from the aircraft. There are two types of Mode 3/A code "alerts": permanent and temporary. A permanent alert is a form of emergency declaration – the Mode 3/A code has been changed to 7700_8, 7600_8, or 7500_8. Any other Mode 3/A code change is classed as a temporary alert indicating that the Mode 3/A code has been changed to a non-emergency value. Note that the alert and SPI conditions are maintained for 18 seconds after they occur.

The FS encoding is defined in the following table.

Table 5-1: Surveillance Status Codes and Definitions

FS Code	Flight Status condition
0	Airborne, No alert, No SPI
1	On the ground, No alert, No SPI
2	Airborne, Alert, No SPI
3	On the ground, Alert, No SPI
4	Airborne, Alert, SPI
5	On the Ground, Alert, SPI
6,7	Reserved

The "alert" portion of flight status can be validated by comparing the Mode 3/A code received by sensor surveillance against the extracted FS value.

Error condition:	ELS Flight Status Data Mode 3/A "alert" invalid; the Mode 3/A code has not changed.

Validation of the airborne/on-the-ground portion of flight status may be performed using a source of ground speed (this may be smoothed/tracked surveillance positional data) and aircraft altitude change. If the ground speed is greater than 100 knots and the altitude has increased more than 100 feet, then the aircraft has become airborne.

Error condition:	ELS Flight Status Data indicates on-ground when the state data indicate that the aircraft is actually airborne (or vice versa).

5.1.2 Flight Identification (Register 20_{16})

If the flight identification text string is available from an external source, (e.g., the aircraft's flight plan) then the decoded text string from register 20_{16} must match it exactly. (See section 2.6 Table 2-1 for the definition of the text string character set.)

Error condition:	Flight Identification data in ELS register 20_{16} does not match flight identification in submitted flight plan.

5.2 EHS Data Validation

If the EHS compliance tests described in section 3 have been successfully passed, then the following data validation tests are to be performed using available external sources of surveillance data. Such sources could include the position reports generated by a Mode S ground sensor. Smoothing (tracking) software may be required to calculate horizontal and vertical velocities from the position reports. The magnetic north deviation value to be used at the sensor site is required in order to compute angles referenced to both true and magnetic north. Validating airspeed and aircraft heading would require knowledge of the wind field, or would require participation in the testing by the pilot (who would fly the aircraft in a predetermined flight path). Local air temperature information would also be needed.

5.2.1 Track and Turn Report (Register 50_{16})

If the Track and Turn Report (EHS register 50_{16}) is configured in the avionics and all its compliance tests from section 3 above have been passed, then the following data validation tests should be performed.

5.2.1.1 Roll Angle

If the status bit for this data field (bit 1) in register 50_{16} is set, then the signed roll angle field should be compared to an estimate of the aircraft's roll angle calculated from its turn rate and speed (derived from smoothed/tracked surveillance reports). The speed value to be used in this calculation is actually airspeed, which may differ from ground speed as a function of the local wind field and air temperature. If available, the "true airspeed" subfield value in this register (see section 5.2.1.5 below) may be employed. A crude comparison would simply equate right turns with right roll, and vice versa. A better comparison would compare the reported roll angle with the computed roll angle based on speed and turn rate.

Assuming that the aircraft is in a level and uniform turn, the relationship between roll angle 'ø' and the aircraft's true airspeed 'V" and turn rate 'w' is given by:

$$ø = \tan^{-1} \{(V * w) / g\}$$

where 'g' is the standard acceleration due to gravity. The aircraft's turn rate 'w' is obtained from the track angle rate as validated in section 5.2.1.4 below (converted to radians per unit time). The aircraft's true airspeed cannot be validated directly, since it is affected by local winds as discussed in section 5.2.1.5 below. The aircraft's ground speed, however, can be validated as described in section 5.2.1.3 below.

Given that the ground speed has been validated, the true airspeed data will be assumed as valid here. Hence, given that ground speed, true airspeed, and track angle rate values are available in register 50_{16}, and the ground speed and track angle rate have been validated, then the roll angle can be validated. If the required data fields in register 50_{16} are not available or their validation fails, then no further validation of roll angle (other than the basic "right turn equals right roll" test) can be performed.

The thresholds for passing the roll angle validation test may be computed from the validation error sigmas derived for speed (see appendix A, subsection 5) and heading rate (see appendix A, subsection 6). Denoting the speed sigma "$sigma_{speed}$" and the heading rate sigma "$sigma_{heading\text{-}rate}$", then the testing thresholds for roll angle "ø" are given by:

$$ø_{max} = \tan^{-1} \{((V + (n * sigma_{speed})) * (w + (n * sigma_{heading\text{-}rate}))) / g\}$$

$$ø_{min} = \tan^{-1} \{((V - (n * sigma_{speed})) * (w - (n * sigma_{heading\text{-}rate}))) / g\}$$

where "n" is the constant parameter for the allowable number of standard deviations permitted for validation testing (typically 3).

Error condition:	**Roll Angle field in EHS register 50_{16} is inconsistent with aircraft state data derived from independent ground-based surveillance.**

5.2.1.2 True Track Angle

If the status bit for this data field (bit 12 in register 50_{16}) is set, then the signed track angle field should be compared to an estimate of the ground track angle (calculated with respect to true north) derived from tracked or smoothed surveillance data. The threshold for passing this test is calculated using the algorithm described in appendix A, subsection 4 of this project memorandum.

Error condition:	**True Track Angle field in EHS register 50_{16} is inconsistent with aircraft state data derived from independent ground-based surveillance.**

5.2.1.3 Ground Speed

If the status bit for this data field (bit 24 in register 50_{16}) is set, then the ground speed field should be compared to an estimate of the ground speed derived from tracked or smoothed surveillance data. The threshold for passing this test is calculated using the algorithm described in appendix A, subsection 5 of this project memorandum .

Error condition:	**Ground Speed field in EHS register 50_{16} is inconsistent with aircraft state data derived from independent ground-based surveillance.**

5.2.1.4 Track Angle Rate

If the status bit for this data field (bit 35 in register 50_{16}) is set, then the signed track angle rate field should be compared to an estimate of the ground track angle rate (with respect to true north) derived from tracked or smoothed surveillance data. This could be derived from the smoothed rate of change of the ground track angle (see section 5.2.1.2 above). The threshold for passing this test is calculated using the algorithm described in appendix A, subsection 6 of this project memorandum.

Error condition:	**True Track Angle Rate field in EHS register 50_{16} is inconsistent with aircraft state data derived from independent ground-based surveillance.**

5.2.1.5 True Airspeed

The "true airspeed" subfield value cannot be directly derived from the tracked surveillance data – that gives ground speed, not airspeed; airspeed is dependent on local winds, air temperature, and altitude. To validate the true airspeed subfield, the test aircraft would be directed to fly straight and level at a series of selected airspeeds. The extracted airspeed would be compared to the airspeed being flown. Alternatively, the true airspeed could be approximated using the measured ground speed over a closed loop course (to average out wind effects) and taking the altitude and temperature effects into account. (Note: the air temperature would be obtained from the test aircraft.)

5.2.2 Heading and Speed Report (Register 60_{16})

If the Track and Turn Report (EHS register 60_{16}) is configured in the avionics and all its compliance tests from section 3 above have been passed, then the following data validation tests should be performed

5.2.2.1 Magnetic Heading

If the status bit for this data field (bit 1 in EHS register 60_{16}) is set, then the signed magnetic heading field can be compared to an estimate of the aircraft's heading (with respect to magnetic north) derived from tracked or smoothed surveillance data. This estimate could be derived from the smoothed rate of change of the aircraft's velocity. This comparison to surveillance data can only be done if an estimate of the current local wind field is known. Alternatively, the pilot could report (by voice) the magnetic heading being flown. The threshold for passing this test is calculated using the algorithm described in appendix A, subsection 4 of this project memorandum.

Error condition:	**Magnetic Heading field in EHS register 60_{16} is inconsistent with aircraft state data derived from independent ground-based surveillance.**

5.2.2.2 Indicated Airspeed

The "indicated airspeed" subfield value cannot be directly derived from the tracked surveillance data – that gives ground speed, not airspeed; indicated airspeed is dependent on local winds, air temperature, and altitude. To validate the indicated airspeed subfield, the test aircraft would be directed to fly straight and level at a series of selected airspeeds. The extracted airspeed would be compared to the airspeed being flown. Alternatively, the indicated airspeed could be approximated using the measured ground speed over a closed loop course (to average out wind effects) and taking the altitude and temperature effects into account. (Note: the air temperature would be obtained from the test aircraft.)

5.2.2.3 Mach

The "Mach number" subfield value cannot be directly derived from the tracked surveillance data – that gives ground speed, not airspeed - mach number is dependent on local winds and temperature (since temperature affects the speed of sound). To validate the Mach number subfield, the test aircraft would be directed to fly straight and level at a series of selected Mach numbers. The extracted Mach number would be compared to the airspeed being flown. Alternatively, the Mach number could be approximated using the measured ground speed over a closed loop course (to average out wind effects) and taking the altitude and temperature effects into account. (Note: the air temperature would be obtained from the test aircraft.)

5.2.2.4 Barometric Altitude Rate

If the status bit for this data field (bit 35 in register 60_{16}) is set, then the signed barometric altitude rate field should be compared to an estimate of the aircraft's altitude rate derived from tracked or smoothed surveillance data. This could be derived from the smoothed rate of change of the aircraft's reported barometric altitude. Note that the altitude rate for aircraft reporting 100-foot quantized altitudes should be smoothed using a special multi-state tracker developed for use in ACAS and "Traffic Information Service" (TIS) applications. A separate tracker is defined for aircraft reporting 25-foot quantized altitudes. The threshold for passing this test may be approximated by dividing the altitude quantization by the time between altitude measurements. For 100-foot quantization and the approximately 5-second update period of a Mode S terminal sensor, this yields 1200 feet/minute as an upper bound on altitude rate indeterminacy. (Note: ACAS and TIS use the value 500 feet/minute as the threshold for "level flight".) For purposes of data validation, a testing threshold of 1000 feet/minute would be appropriate for altitudes quantized to 100 feet. If 25-foot altitude data is available (e.g., output from a surveillance sensor supporting ASTERIX output), a testing threshold of 250 feet/minute would be appropriate.

Error condition:	**Barometric Altitude Rate field in EHS register 60_{16} is inconsistent with the reported rate of change in the aircraft's barometric altitude.**

5.2.2.5 Inertial Vertical Velocity

If the status bit for this data field (bit 46 in register 60_{16}) is set, then the signed inertial vertical velocity field should be compared to an estimate of the aircraft's altitude rate derived from tracked or smoothed surveillance data. This could be derived from the smoothed rate of change of the aircraft's reported barometric altitude. Note that the altitude rate for aircraft reporting 100-foot quantized altitudes should be smoothed using a special multi-state altitude tracker developed for use in ACAS and "Traffic Information Service" (TIS) applications. A separate altitude tracker is defined for aircraft reporting 25-foot quantized altitudes. The threshold for passing this test is the same as that for barometric altitude rate as described in section 5.2.2.4 above.

Error condition:	**Inertial Vertical Velocity field in EHS register 60_{16} is inconsistent with the rate of altitude change computed using altitude data from ground-based surveillance.**

5.3 ADS-B Data Validation

If the ADS-B compliance tests described in section 4 above have been successfully passed, then data validation tests described in this section are to be performed using available external sources of surveillance data. Such sources could include the position reports generated by a Mode S ground sensor. Smoothing (tracking) software may be required to calculate horizontal and vertical velocities from the position reports . The magnetic north deviation value to be used at the sensor site may be required in order to compute angles referenced to true north. Validating airspeed and aircraft heading would require knowledge of the wind field, or would require participation in the testing by the pilot (who would fly the aircraft in a predetermined flight path). Local air temperature information would also be needed.

5.3.1 Airborne Position (Register 05_{16})

If the avionics are configured to support this register (i.e., bit 34 of register 10_{16} and bit 1 of register 17_{16} are set) and all its compliance tests from section 4 above have been passed, then the contents of this register are compared to positional data obtained from an external surveillance source. An external source of the aircraft's Mode 3/A identity code and "special position indicator" (SPI) bit are required to validate the "surveillance status" field (e.g., the surveillance FS field as described in section 5.1.1 above). In some cases, the current local barometric altitude conversion factor, or the latitude and longitude of the external surveillance sensor will be needed as well.

5.3.1.1 Surveillance Status

The surveillance status field value is determined from the SPI and Mode 3/A code data as given in the following table. Note: the SPI and Mode 3/A code data are available in the Mode S surveillance FS field (see section 5.1.1 above).

Table 5-2: Surveillance Status Codes and Definitions

Surveillance Status Code	Surveillance Status condition
0	No condition information
1	Emergency condition (Mode 3/A code = 7700_8, 7600_8, or 7500_8)
2	Temporary alert (Mode 3/A code changed, but not emergency code)
3	SPI bit set

Note that cases 1 and 2 take precedence over case 3.

Error condition:	**Surveillance Status field in ADS-B register 05_{16} is inconsistent with the surveillance status values in the Mode S Surveillance data.**

5.3.1.2 Altitude

If the altitude field in register 05_{16} is nonzero, then the altitude value should be compared to the altitude obtained from the external surveillance source. The altitude field might be either in barometric 25-foot quantization, barometric 100-foot quantization, or GNSS (GPS) units. Note: the format type-code value (the first 5 bits of the register) indicates the type of altitude. Format type-code values 9 through 18 indicate barometric altitudes. Format type-codes 20 through 23 indicate GNSS altitudes. The altitude field value and the external surveillance source altitude must be converted to matching units (possibly applying the local barometric conversion factor) and compared. The threshold for passing this test would be twice the altitude quantization available in the surveillance data.

Error condition:	**Altitude field in ADS-B register 05_{16} is inconsistent with the altitude data obtained by ground-based surveillance.**

5.3.1.3 Latitude

If the format type-code value (the first 5 bits of register 05_{16}) indicates that position data is available (nonzero value), then the latitude and longitude fields in the register (along with the CPR format bit) are decoded using the “Compact Position Reporting” (CPR) airborne local decoding algorithm. See [5], [6], or [7] for the definition of the CPR algorithm. (Note: this algorithm assumes that the latitude and longitude of the sensor receiving the squitter are known.) The decoded aircraft’s latitude is compared to the aircraft’s latitude computed from the external surveillance source. The threshold for passing this test is calculated using the algorithm described in appendix A, subsection 3 of this project memorandum.

Error condition:	**Latitude field in ADS-B register 05_{16} is inconsistent with position data derived from data obtained by ground-based surveillance.**

5.3.1.4 Longitude

If the format type-code value (the first 5 bits of the register 05_{16}) indicates that position data is available (nonzero value), then the latitude and longitude fields in the register (along with the CPR format bit) are decoded using the “Compact Position Reporting” (CPR) airborne local decoding algorithm. See [5], [6], or [7] for the definition of the CPR algorithm. (Note: this algorithm assumes that the latitude and longitude of the sensor receiving the squitter are known.) The decoded aircraft’s longitude is compared to the aircraft’s longitude computed from the external surveillance source. The threshold for passing this test is calculated using the algorithm described in appendix A, subsection 3 of this project memorandum.

Error condition:	**Longitude field in ADS-B register 05_{16} is inconsistent with position data derived from data obtained by ground-based surveillance.**

5.3.2 Surface Position (Register 06_{16})

If the avionics are configured to support this register (i.e., bit 34 of register 10_{16} and bit 2 of register 17_{16} are set) and all its compliance tests from section 4 above have been passed, then the contents of this register are compared to positional data obtained from an external surveillance source. In some cases, the latitude and longitude of the external surveillance sensor will be needed. Smoothing (tracking) software may be required to calculate horizontal velocities from the position reports. The magnetic north deviation value to be used at the sensor site may be required in order to compute angles referenced to true north.

5.3.2.1 Movement

If the 7-bit movement field value (bits 6 through 12 in register 06_{16}) is nonzero, then the encoded ground speed should be decoded as shown in the following table. Note that the quantization used is non-linear with different quantization for each ground speed range. The decoded ground speed field should be compared to an estimate of the ground speed derived from tracked or smoothed surveillance data. The threshold for passing this test is calculated using the algorithm described in appendix A, subsection 5 of this project memorandum.

Table 5-3: Surface Position "Movement" Encoding

Decoding	Meaning	Quantization
0	No data available	----
1	Aircraft stopped (< 0.125 knots)	----
2-8	0.125 knots < speed ≤ 1 knot	0.125 knots
9-12	1 knot < speed ≤ 2 knots	0.25 knots
13-38	2 knots < speed ≤ 15 knots	0.5 knots
39-93	15 knots < speed ≤ 70 knots	1 knot
94-108	70 knots < speed ≤ 100 knots	2 knots
109-123	100 knots < speed ≤ 175 knots	5 knots
124	≥ 175 knots	----
125	Reserved	----
126	Reserved	----
127	Reserved	----

Error condition:	**Movement field in ADS-B register 06_{16} is inconsistent with movement data derived from position data obtained by ground-based surveillance.**

5.3.2.2 Ground Track

If the status bit for this data field (bit 13 in register 06_{16}) is set, then the signed ground track field should be compared to an estimate of the aircraft's ground track (with respect to true north) derived from tracked or smoothed surveillance data. The threshold for passing this test is calculated using the algorithm in appendix A, subsection 4 of this project memorandum.

Error condition:	**Ground Track field in ADS-B register 06_{16} is inconsistent with movement data derived from position data obtained by ground-based surveillance.**

5.3.2.3 Latitude

If the format type-code value in the first 5 bits of the register indicates that position data is available (value in the range 5 through 8), then the latitude and longitude fields in the register (along with the "CPR format bit) are decoded using the "Compact Position Reporting" (CPR) surface local decoding algorithm. See [5], [6], or [7] for the definition of the CPR algorithm. (Note: this algorithm assumes that the latitude and longitude of the sensor receiving the squitter are known.) The decoded aircraft's latitude is compared to the aircraft's latitude computed from the external surveillance source. The threshold for passing this test is calculated using the algorithm from appendix A, subsection 3 of this project memorandum.

Error condition:	**Latitude field in ADS-B register 06_{16} is inconsistent with position data derived from data obtained by ground-based surveillance.**

5.3.2.4 Longitude

If the format type-code value in the first 5 bits of the register indicates that position data is available (value in the range 5 through 8), then the latitude and longitude fields in the register (along with the "CPR format bit) are decoded using the "Compact Position Reporting" (CPR) surface local decoding algorithm. See [5], [6], or [7] for the definition of the CPR algorithm. (Note: this algorithm assumes that the latitude and longitude of the sensor receiving the squitter are known.) The decoded aircraft's longitude is compared to the aircraft's longitude computed from the external surveillance source. The threshold for passing this test is calculated using the algorithm from appendix A, subsection 3 of this project memorandum.

Error condition:	**Longitude field in ADS-B register 06_{16} is inconsistent with position data derived from data obtained by ground-based surveillance.**

5.3.3 Aircraft Identification and Category (Register 08_{16})

If the avionics are configured to support this register (i.e., bit 34 of register 10_{16} and bit 4 of register 17_{16} are set) and all its compliance tests from section 4 above have been passed, then the contents of the aircraft identification and category may be compared against information obtained from an external source (such as the flight plan). The decoded aircraft identification character string from register 08_{16} must match the aircraft type in the external data. (See section 2.6 Table 2-1 for the definition of the character set.)

Error condition:	**Flight Identification data in ADS-B register 08_{16} does not match the flight identification in flight plan data obtained from an external source.**

The first 5 bits of the register contents (the format type-code) may take on 4 legal values as described in Table 4-1 in section 4.9 above. The value '1' is reserved, and the value '2' refers to fixed installations or surface vehicles (not aircraft). The value '3' refers to nonstandard light aircraft. Hence, only the value '4' should appear in the format type code of register 08_{16} for normal aircraft.

Error condition:	**Flight Identification format type-code in ADS-B register 08_{16} is not correct for a normal aircraft.**

5.3.4 Airborne Velocity (Register 09_{16})

If the avionics are configured to support this register (i.e., bit 34 of register 10_{16} and bit 25 of register 17_{16} are set) and all its compliance tests from section 4 above have been passed, then the contents of this register are compared to positional data obtained from an external surveillance source. The magnetic north deviation value to be used at the sensor site may be required. Note that the altitude rate for aircraft reporting 100-foot quantized altitudes should be smoothed using a special multi-state altitude tracker developed for use in ACAS and "Traffic Information Service" (TIS) applications. A separate altitude tracker is defined for aircraft reporting 25-foot quantized altitudes.

5.3.4.1 Horizontal Velocity

The subtype field (bits 6 through 8) subdivides the horizontal velocity measurement process into four cases. Subtypes 1 and 2 use Cartesian "velocity over ground" components, while subtypes 3 and 4 use polar "magnetic heading and airspeed" components. (Subtypes 5 through 7 are reserved.) Within each category, speeds are divided into a normal range (< 1024 knots) and supersonic (≥ 1024 knots).

5.3.4.1.1 Velocity Over Ground

In this case, velocity is indicated using two signed Cartesian values – east-west velocity and north-south velocity. If either of the values is zero, this indicates that no velocity data is present. If velocity data is present and the subtype is 1, (indicating the normal speed range) then the quantization is 1 knot. If velocity data is present and the subtype is 2, (indicating the supersonic speed range) then the quantization is 4 knots. In either case, the speed is given by:

Speed = (code – 1) * quantization

The speed components decoded from register 09_{16} should be compared to the velocity values obtained from an external source of surveillance data (perhaps with the application of a smoother/tracker algorithm) converted to Cartesian components. The threshold for passing this test is calculated using the algorithm in appendix A, subsection 5 of this project memorandum.

Error condition:	**Velocity Over Ground field in ADS-B register 09_{16} is inconsistent with movement data derived from position data obtained by ground-based surveillance.**

5.3.4.1.2 Magnetic Heading and Airspeed

In this case, velocity is indicated using a signed magnetic heading field and an airspeed field. If the status bit for magnetic heading (bit 14) is set, then the magnetic heading field should be compared to an estimate of the aircraft's heading (with respect to magnetic north) derived from tracked or smoothed surveillance data. This could be derived from the smoothed rate of change of the aircraft's velocity. This comparison to surveillance data can only be done if an estimate of the current local wind field is known. The threshold for passing this test is calculated using the algorithm in appendix A, subsection 5 of this project memorandum. Alternatively, the pilot could report (by voice) the magnetic heading being flown.

Error condition:	**Magnetic Heading field in ADS-B register 09_{16} is inconsistent with heading data derived from position data obtained by ground-based surveillance.**

Bit 25 in the register indicates whether the airspeed is “indicated” (IAS) or “true” (TAS). If the airspeed value is zero, this indicates that no velocity data is present. If velocity data is present and the subtype is 3, (indicating the normal speed range) then the quantization is 1 knot. If velocity data is present and the subtype is 4, (indicating the supersonic speed range) then the quantization is 4 knots. In either case, the speed is given by:

Speed = (code – 1) * quantization

The airspeed value (indicated or true) cannot be directly derived from the tracked surveillance data – that gives ground speed, not airspeed. (Both indicated and true airspeed are dependent on local winds, while indicated airspeed is also dependent on air temperature, and altitude.) To validate the airspeed subfield, the test aircraft would be directed to fly straight and level at a series of selected airspeeds. The extracted airspeed would be compared to the airspeed being flown. Alternatively, the airspeed could be approximated using the measured ground speed over a closed loop course (to average out wind effects) and taking the altitude and temperature effects into account. (Note: the air temperature would be obtained from the test aircraft.)

5.3.4.2 Vertical Rate

If the signed vertical rate field is nonzero, then the signed vertical rate value (in feet per minute) is to be compared to the smoothed altitude rate generated from an external source of surveillance data. The threshold for passing this test is the same as that for barometric altitude rate as described in section 5.2.2.4 above.

Error condition:	**Vertical Rate field in ADS-B register 09_{16} is inconsistent with the rate of altitude change computed using altitude data from ground-based surveillance.**

6 Mode S Transponder Anomaly Reports

Application of the validation tests described in the preceding sections will result in the generation of anomaly reports for those aircraft that fail any of the compliance tests. Multiple reports may be generated for a given aircraft, depending on the state of its avionics. The availability of external data sources (such as independent ground surveillance or the aircraft's flight plan) will determine whether some of the validation tests can be performed. Note that some of the data validation tests require cooperation from the pilot.

Each output report will include the following data items:

(a) Mode S address of the aircraft;

(b) Date and time tag of the Mode S register extraction (accurate to the second);

(c) Error message text string (from sections 2 through 5); and

(d) The field value extracted from the Mode S register or transponder reply and the "truth" value from external data sources that was compared against it, both converted to appropriate common units.

Appendix A -- Calculation of Measurement Error Sigmas for Radar-Derived Surveillance Data

A-1. Introduction

This appendix provides the algorithms required to determine the measurement accuracy derivable from radar-based surveillance data. When radar-based surveillance data is used to validate Mode S "enhanced surveillance" (EHS) or "automatic dependent surveillance via broadcast" (ADS-B) data values, these algorithms should be used to determine the accuracy thresholds to be employed for the validation comparisons for the respective data items. The algorithms described in this appendix calculate the data error distribution "sigma" – the standard deviation of the value expected for the particular variable. The validation thresholds would simply be a multiple of the calculated sigma for the variable. A multiplier value of 3 is typically employed, since data errors in excess of three standard deviations are rare.

The equations used in subsections 3 through 5 of this appendix were derived from [8]. A simplifying assumption has been made that the sources of radar surveillance data utilize simple Kalman filters or tracker algorithms (e.g., 2-point interpolators or alpha-beta smoothers). This simplifying assumption holds true for Mode S and other current radar surveillance ground sensors.

Subsection 2 of this appendix defines the basic radar surveillance data inputs and parameters assumed by the later algorithms. Subsection 3 defines the equations used to calculate the positional surveillance error sigmas based on the input radar data. These positional error sigmas would be used in the validation of ADS-B positional data, and are also used in the calculation of further surveillance-derived error sigmas in later sections. Subsection 4 defines the equations used to calculate the error sigma for aircraft heading based on the input radar surveillance data. Subsection 5 defines the equations used to calculate the error sigma for aircraft ground speed based on the input radar surveillance data. Finally, subsection 6 defines the equations used to calculate the error sigma for aircraft heading rate.

A-2. Inputs to the Equations

The equations derived here assume that the sensor measurement errors in the range and azimuth directions are inputs given as parameters of the surveillance radar sensor – denoted as 'SigmaRange' and 'SigmaAzimuth'. SigmaRange is given in nautical miles, while SigmaAzimuth is given in radians. For a typical U.S. civilian Mode S sensor, the value of SigmaRange would be 0.01 nautical miles and the value of SigmaAzimuth would be 0.001 radians. The values of these surveillance sensor parameters would be configuration inputs to the validation testing software.

For each surveillance target report correlated to a given aircraft track, the following input data items are assumed:

- Range: in nautical miles (slant range from the sensor)
- Azimuth: in radians clockwise from true north
- X: in nautical miles from the sensor (ground position, positive eastward)
- Y: in nautical miles from the sensor (ground position, positive northward)
- Altitude: in nautical miles (or feet), typically barometric
- T: time (or scan number)

The Cartesian ground position values 'X' and 'Y' are derived from the measured range, azimuth and altitude. (Note: since the aircraft for which EHS or ADS-B data is available will be Mode S-equipped, a measured altitude should be available and is used to convert slant range to ground range. If no altitude is available, use a default of 0.5 nautical miles or ½ of the slant range, whichever is smaller.) The aircraft track is assumed to maintain the previous values of the report data, as well as previous values of the data sigmas as calculated in subsection 3 below. Also, it is assumed that the time difference (or number of scans) between the current and previous correlation report for the track is known. (Note: the number of scans may be converted to time using the system scan time parameter.)

A-3. Calculations for Sigma-X and Sigma-Y

The following equations are used to calculate the values of the squares of the positional error sigmas in units of nautical miles-squared. Denoted 'SigmaX' and 'SigmaY', these are the positional error sigmas in Cartesian coordinates. Besides their application for checking aircraft positional data, SigmaX and SigmaY are also used in the calculation of the speed and heading error sigma values. There is also a cross-term square (also in units of nautical miles-squared), SigmaXY^2 that will be used in the later calculations of SigmaHeading in section 4 and SigmaSpeed in section 5 of this appendix. (Note that only the radar surveillance range and azimuth measurement inputs are used in these equations.)

$$\text{SigmaX}^2 = (\text{SigmaRange}^2 * \cos(\text{Azimuth})^2) + (\text{Range}^2 * \text{SigmaAzimuth}^2 * \sin(\text{Azimuth})^2)$$

$$\text{SigmaY}^2 = (\text{SigmaRange}^2 * \sin(\text{Azimuth})^2) + (\text{Range}^2 * \text{SigmaAzimuth}^2 * \cos(\text{Azimuth})^2)$$

$$\text{SigmaXY}^2 = [\text{SigmaRange}^2 - (\text{Range}^2 * \text{SigmaAzimuth}^2)] * \sin(\text{Azimuth}) * \cos(\text{Azimuth})$$

The ADS-B positional data is extracted from an aircraft in polar latitude and longitude coordinates, so the positional sigmas need to be converted from the Cartesian coordinates. A simple spherical Earth model may be used for this coordinate conversion. If the radius of the Earth in nautical miles is denoted 'R_E' and the latitude of the radar sensor in radians is denoted as 'S_{lat}', then the following equations may be used to calculate the error sigmas in latitude and longitude (in radians).

$SigmaLatitude = SigmaY / R_E$

$SigmaLongitude = SigmaX / (R_E * \cos(S_{lat}))$

(Note: a more-accurate oblate-spheroid model of the Earth would yield a more-accurate conversion, but is probably unnecessary for the calculation of validation testing thresholds here.)

A-4. Calculation for Sigma-Heading

The equation for '$Sigma_{Heading}$' assumes that there are values for the current Cartesian x-y position as well as the current SigmaX and SigmaY values (and the cross-term SigmaXY value) as calculated in section 3 of this appendix. These values will be denoted with the subscript "current". Similarly, it is assumed that there are saved values for Cartesian x-y position and sigma values for the previous measurement data point -- denoted with the subscript "previous". (If there is only one data report available for a given aircraft track, then the heading error sigma cannot be calculated and should default to 0.)

The following equations generate intermediate terms for the heading error sigma calculation.

$DeltaX = (X_{current} - X_{previous})$

$DeltaY = (Y_{current} - Y_{previous})$

$TermX = DeltaX^2 * (SigmaY^2_{previous} + SigmaY^2_{current})$

$TermY = DeltaY^2 * (SigmaX^2_{previous} + SigmaX^2_{current})$

$TermXY = 2 * DeltaX * DeltaY * (SigmaXY^2_{previous} + SigmaXY^2_{current})$

$Denom = (DeltaX^2 + DeltaY^2)^2$

The following equation yields the heading error sigma value squared in units of radians-squared based on the intermediate values calculated above. Note that there must be a protection in the algorithm against a denominator value of zero (e.g., a non-moving aircraft track). The sigma heading error value should be defaulted to "infinity" for this degenerate case. No heading validation tests can be performed in this default case.

$Sigma_{Heading}^2 = (TermX + TermY - TermXY) / Denom$

A-5. Calculation for Sigma-Speed

The calculation for 'SigmaSpeed' makes the same assumptions on inputs as the calculation for SigmaHeading in subsection 4 of this appendix. The intermediate values "DeltaX" and "DeltaY" are carried over from subsection 4 above. The positional error sigma values are carried over from subsection 3 of this appendix. The following equations derive intermediate values for the calculation of the square of the sigma error for ground speed. The 'DeltaTime' may be computed directly (if report time tags are available) or indirectly from the scan count difference and the radar sensor's scan period parameter. (If there is only one data report available for an aircraft track, then the speed sigma cannot be calculated and should default to 0.)

$$DeltaTime = T_{current} - T_{previous}$$

$$Denom = (DeltaX^2 + DeltaY^2) * DeltaTime^2$$

$$TermX_{current} = (DeltaX^2 * SigmaX^2_{current})$$

$$TermX_{previous} = (DeltaX^2 * SigmaX^2_{previous})$$

$$TermY_{current} = (DeltaY^2 * SigmaY^2_{current})$$

$$TermY_{previous} = (DeltaY^2 * SigmaY^2_{previous})$$

$$TermXY_{current} = (2 * DeltaX * DeltaY * SigmaXY^2_{current})$$

$$TermXY_{previous} = (2 * DeltaX * DeltaY * SigmaXY^2_{previous})$$

$$Term_{current} = TermX_{current} + TermY_{current} + TermXY_{current}$$

$$Term_{previous} = TermX_{previous} + TermY_{previous} + TermXY_{previous}$$

The following equation gives the square of the ground speed error sigma value (in units of nautical miles per scan - squared). Note that there must be a protection against a denominator value of zero (a non-moving track). Set the ground speed error sigma speed value to "infinity" for this case. No speed validation tests can be performed in this default case.

$$Sigma_{Speed}^2 = (Term_{current} + Term_{previous}) / Denom.$$

A-6. Calculations for Sigma-Heading-Rate

Heading rate is defined by the following equation (assuming no change in turn rate over the measurement time). The value of heading from the current measurement and the saved heading from a previous measurement are assumed. (If there is only one data report available for an aircraft track, then the heading rate sigma cannot be calculated and should default to 0.)

$$HeadingRate = (Heading_{current} – Heading_{previous}) / DeltaTime$$

'DeltaTime' is the same value used in the calculation of ground speed in subsection 5 of this appendix. The assumption of no turning acceleration is reasonable for short time periods and typical aircraft maneuvers. (A smoothing filter may be used on the heading values to model turning accelerations more accurately.) The heading error sigma for each heading measurement is assumed to be available as described in section 4 of this appendix. Assuming that the heading error sigma values are independent, the square of the error sigma for heading rate may be given simply as:

$$Sigma_{HeadingRate}^2 = 2*(SigmaHeading_{current} * SigmaHeading_{previous}) / DeltaTime^2$$

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List of Acronyms

ACAS	Airborne Collision Avoidance Equipment
ADS-B	Automatic Dependent Surveillance via Broadcast
ARINC	Aeronautical Radio, Incorporated
ASTERIX	All-purpose Structured Eurocontrol Radar Information Exchange
BDS	Mode S Comm-B Data Selector
CA	Mode S Transponder Capability
CPR	Compact Position Reporting
DF	Mode S Downlink Format
EHS	Enhanced Surveillance
ELS	Elementary Surveillance
FAA	Federal Aviation Administration
FS	Flight Status
GNSS	Global Navigation Satellite System
IAS	Indicated Airspeed
NAC	Navigational Accuracy Category
NUC	Navigational Uncertainty Category
SPI	Special Position Indicator
TAS	True Airspeed
TIS	Traffic Information Service
UAV	Unmanned Aerial Vehicle
USAF	United States Air Force