Consolidated Final Review and Comments for RTCA SC-186 Proposed Final Draft of:

CHANGE #1 to the MINIMUM OPERATIONAL PERFORMANCE STANDARDS FOR 1090 MHz EXTENDED SQUITTER AUTOMATIC DEPENDENT SURVEILLANCE BROADCAST (ADS-B) and TRAFFIC INFORMATION SERVICES BROADCAST (TIS-B) RTCA/DO-260A

Comment #	Comment Author	DO-260A Change #	Comment	Suggested Resolution
1	Gary Furr	New	As a comment against the FAA Broadcast Services Ground System Specification, it has been pointed out that it will not be clear to a ground system when an emergency event has been resolved based on the receipt of information encoded in a Mode Status Report, since the last paragraph of §2.2.8.2.9 implies that if no Emergency/Priority Status data has been received since the last Mode Status Report, that ALL ZEROs would be transmitted in the next Mode Status Report. This needs to be clarified.	Proposed Resolution: (1) In DO-260A, §2.2.8.2.1.2, replace the last two sentences of this paragraph with the following: Only the six most significant bits of the subfield are currently assigned. The remaining 2 bits are reserved for future use. (2) In DO-260A, Table 2-90, on the MS Report Line Item #6, for the Emergency/Priority Status, change the "No" to "Yes" and indicate that the Validity Flag Assignment is for Bit #2. In the "Yes" column, also add the notation that "If an update has not been received within 100 seconds, via an Extended Squitter Aircraft Status Message or a Target State and Status Message, then this report element is not considered valid." (3) In DO-260A, §2.2.8.2.9, replace the third paragraph with the following: 'When valid "Emergency/Priority Status" data is not available (i.e., has not been received within the past 100 seconds as per Table 2-102, Note #5), then the Emergency / Priority Status data sent to the user application **shall** be set to ALL ZEROs and flagged as being "invalid" as per Table 2-90.' (4) In DO-260A, Table 2-102, add a new Note #5 with the following: '*Required if an Extended Squitter Aircraft Status Message (TYPE=28, Subtype=1) and/or a Target State and Status Message (TYPE=29, Subtype=0) has been received within the*

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				past 100 seconds.' Change the reference in Table 2-102 on the "Emergency/Priority Status Line to point to Note #5 for both Surface and Airborne. (5) In DO-260A, §2.4.8.2.9, add onto the end of both Steps #3 and #4 the following: 'Terminate the input for the Aircraft Status Message and verify that the Mode Status Report continues to contain the last reported state of the Emergency / Priority Status for 100 seconds. After a period of 100 seconds, verify that the Emergency/Priority Status data field in the Mode Status Report contains ALL ZEROs, and that the Emergency/Priority Status Validity Flag has been set in byte 3, bit 2 (see Table 2-90) of the Mode Status Report to indicate that the data is not valid.' **WG-3 Agrees with this change and directs it to be implemented in Change 1.**
2	Gary Furr	New	While reviewing the cases of the transmission of the Emergency/Priority Status, in both the Aircraft Status Messages and the Target State and Status Messages, it became clear that there were insufficient test cases in DO-260A to ensure that ground systems receive the proper information at the correct time and that it is clear what the validity of that information is. It is therefore believed that some test procedures need to be added in §2.4.9.1.2.	Proposed Resolution: Replaced the existing text of §2.4.9.1.2 with the following: The test procedures that are required to validate the requirements of §2.2.9.1.2 are included in §2.4.8.2.1 through §2.4.8.2.18, and in the test steps that are identified below. Purpose/Introduction: Table 2-102 presents the required elements of a Mode Status Report. The Notes below the table indicate that several of those elements will continue to be reported in the Mode Status Report for a time period after the specifically referenced information has last appeared in its respective ADS-B Message. The following test procedure steps are intended to test that function. Measurement Procedures: Step 1: Perform the test steps in §2.4.8.2.6. Terminate the input for the Aircraft Identification Message and verify that the Mode Status Report continues to contain the last reported state of the Call Sign for 200 seconds. Step 2: Perform the test steps in §2.4.8.2.7. Terminate the input for

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				the Aircraft Identification Message and verify that the Mode Status Report continues to contain the last reported state of the Emitter Category for 200 seconds. Step 3: Perform the test steps in §2.4.8.2.8. Terminate the input for the Aircraft Operational Status Message and verify that the Mode Status Report continues to contain the last reported state of the A/V Length and Width Codes for 100 seconds. Step 4: Perform the test steps in §2.4.8.2.10. Terminate the input for the Aircraft Operational Status Messages and/or the Target State and Status Messages, and verify that the Mode Status Report continues to contain the last reported state of the Capability Class Codes for 100 seconds. Step 5: Perform the test steps in §2.4.8.2.11. Terminate the input for the Aircraft Operational Status Messages and/or the Target State and Status Messages, and verify that the Mode Status Report continues to contain the last reported state of the Operational Mode Codes for 100 seconds. Step 6: Perform the test steps in §2.4.8.2.12. Terminate the input for the Aircraft Operational Status Messages and/or the Target State and Status Messages, and verify that the Mode Status Report continues to contain the last reported state of the NAC_P for 100 seconds. Step 7: Perform the test steps in §2.4.8.2.13. Terminate the input for the Airborne Velocity Messages and verify that the Mode Status Report continues to contain the last reported state of the NAC_V for 100 seconds. Step 8: Perform the test steps in §2.4.8.2.14. Terminate the input for the Aircraft Operational Status Messages and/or the Target State and Status Messages, and verify that the Mode Status Report continues to contain the last reported state of the SIL for 100 seconds.

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				Step 9: Perform the test steps in §2.4.8.2.17. Terminate the input for the Aircraft Operational Status Messages and verify that the Mode Status Report continues to contain the last reported state of the True/Magnetic Heading for 100 seconds Step 10: Perform the test steps in §2.4.8.2.18. Terminate the input for the Airborne Velocity Messages and verify that the Mode Status Report continues to contain the last reported state of the Vertical Rate Type for 100 seconds. **WG-3 Agrees with this change and directs it to be implemented in Change 1.**
3	Chuck Manberg ACSS	Global	Remove "**Shall Not**" Requirements – cannot Test.	Replace "**shall not**" with "**will not**." **WG-3 Disagrees with this comment, and after reviewing the cases where this exists in the proposed "Change 1" document, the Working Group decided to retain all "shall not" requirements.**
4	Don Walker/ Brandao Honeywell	1.2	Honeywell wants to make it clear that changes to the minimum output power for class A3 equipment may incur additional expense upon DO-260A compliance for the segment of the Mode S population of aircraft wishing to achieve A3 transmit classification. In nominal operating conditions, a large percentage of existing transponders in the fleet may meet this increased output power requirement. However, units were not necessarily qualified, nor are necessarily maintained, to meet this minimum output power requirement. Honeywell has a concern that the ADS-B business case studies which have been conducted by the FAA have assumed that hardware modifications to the Mode S transponder would not be required for ADS-B equipage. If A3 classification is required, at the minimum output power of 53 dBm, then that assumption will no longer hold true. Operators may have to upgrade transponder hardware, or reduce the	Honeywell recommends deferring changing this from a recommendation to a requirement until it can be verified this is the final solution. **After discussion, Honeywell observes that the 1090ES community believes that the 200 watts are necessary in order to meet the ADS-B MASPS requirements, and therefore this change will continue. It was agreed that the JHU-APL 1090ES analysis paper would be labeled Working Paper WP21-04 and referenced in the minutes of Meeting 21 and posted on the 1090ES ADS-B web site for reference.**

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			cable loss to meet this requirement. Honeywell understands the increase in the minimum output power is an attempt to address the issues of range degradation in a high fruit environment. The increase in minimum output power proposed does improve the performance for longer range applications over higher density fruit environments such as LA or Frankfurt. However, the increased requirements of A3 performance over these "high interference environments" will still not meet the DO-242A MASPS A3 range performance requirements. Refer to DO-260A Appendix P Table P-1.	
5	Nolan Van Foeken Garmin	1.5	The proposed section 2.2.3.2.1.2, item (4) seems to omit the notion that radio height, ground speed and airspeed can override an “on-ground” indication from a weight-on-wheels or similar means of air/ground determination	Clearly specify the logic that is verified in section 2.4.3.2.1.2.2, Step 4 (DO-260A Change #1.35). The idea is that the aircraft is assumed to be "airborne" IF (NOT weight-on-wheels OR (radio_height AND groundspeed AND airspeed)) **WG-3 agrees that the override condition is actually described in subparagraph “d” and is left as is and was not included in the proposed change. Therefore this comment was rejected.**
6	James Maynard Garmin (1)	New	**Minor editorial comment:** In the DO-260A base document, the second paragraph of text under §1.4, ADS-B Functions, describes only the ADS-B Message Generation Function, and so should more logically be placed after the heading for §1.4.1, ADS-B Message Generation Function.	If DO-260A is ever published with the Change 1 changes incorporated, move the heading, “$1.4.1 ADS-B Message Generation Function” to come just before the second paragraph of the present §1.4. **Jim Maynard agrees to withdraw this comment. The paragraph was actually an introductory paragraph and should remain where it is.**
7	James Maynard Garmin (2)	New	**Editorial comment:** In the DO-260A base document, §1.4.1.3 imposes a requirement (marked by a boldface “**shall.**”) Are not requirements supposed to be in §2 or §3?	If DO-260A is ever published with the Change 1 changes incorporated, delete the auxiliary verb “shall” from the first sentence of §1.4.1.3. **WG-3 agrees with the comment and agrees to delete the word “shall” from this paragraph.**

<table>
<tr><th>Comment #</th><th>Comment Author</th><th>DO-260A Change #</th><th>Comment</th><th>Suggested Resolution</th></tr>
<tr><td>8</td><td>James Maynard

Garmin (3)</td><td>1.4</td><td>The Rebroadcast of ADS-B messages on a data link other than the original data link is one of the functions of the TIS-B service. Thus, 1090 MHz extended squitters that have DF=18 and CF=6 <u>are</u> TIS-B messages and should be processed as such.</td><td>Change the last sentence in the replacement paragraph at the end of §2.2.3.2 to read, “Receiving equipment shall not process as TIS-B Messages any Extended Squitter receptions in which DF is not equal to 18, or in which CF is not in the range from 2 to 6.”

After discussion, WG-3 agreed to make an entry into section 1.1 and Appendix B of DO-260A, via new changes, indicating the difference in TIS-B and ADS-R. The specific suggestion to change the last sentence in the proposed replacement paragraph was rejected by the Working Group as potentially causing confusion regarding the use of ADS-B Message formats for Rebroadcast messages.</td></tr>
<tr><td>9</td><td>James Maynard

Garmin (4)</td><td>1.6</td><td>The Rebroadcast of ADS-B messages on a data link other than the original data link is one of the functions of the TIS-B service. It is not useful to invent a third sub-class (besides ADS-B messages and TIS-B messages) of DF=18 messages.</td><td>Modify the replacement for Table 2-11 to classify the DF=18, CF=6 case as a kind of TIS-B message:
<table>
<tr><th colspan="2">Coding</th><th colspan="2" rowspan="2">Meaning</th></tr>
<tr><th>(binary)</th><th>(decimal)</th></tr>
<tr><td>000</td><td>0</td><td>ADS-B Message</td><td>AA field holds the transmitting ADS-B Participant’s 24-bit ICAO address</td></tr>
<tr><td>001</td><td>1</td><td rowspan="7">TIS-B and ADS-R Message</td><td>AA field holds another king od address for the transmitting ADS-B Participant: …</td></tr>
<tr><td>010</td><td>2</td><td>Find TIS-B message using ICAO 24-bit address</td></tr>
<tr><td>011</td><td>3</td><td>Coarse TIS-B Airborne Position and Velocity Message</td></tr>
<tr><td>100</td><td>4</td><td>Reserved for TIS-B Management Message</td></tr>
<tr><td>101</td><td>5</td><td>Fine TIS-B Message using non-ICAO 24-bit address</td></tr>
<tr><td>110</td><td>6</td><td>Rebroadcast of an ADS-B Message from an alternate data link ….</td></tr>
<tr><td>111</td><td>7</td><td colspan="2">Reserved</td></tr>
</table>
WG-3 Agreed as modified. Codes 2 through 6 will be referred to as TIS-B and ADS-R Messages and the title of the table will be changed to agree with this.</td></tr>
</table>

<table>
<tr><th>Comment #</th><th>Comment Author</th><th>DO-260A Change #</th><th>Comment</th><th>Suggested Resolution</th></tr>
<tr><td>10</td><td>James Maynard

Garmin (5)</td><td>1.7</td><td>In the replacement Table 2-13, in the row for the DF=18, CF=7 case, the text in the “AA Field Contents” cell contains a sentence fragment.</td><td>The text in that cell should read, “Reserved for future standardization; AA field does not necessarily exist in messages for which DF = 18 and CF = 7.”
<u>WG-3 Agreed:</u> Edit made as suggested.</td></tr>
<tr><td>11</td><td>James Maynard

Garmin (6)</td><td>1.8</td><td>Although the paragraph before Table2-14 and the title of Table 2-14 are to be changed, the Note that occurs between that paragraph and that table should be retained.</td><td>Retain the Note before Table 2-14.

<u>WG-3 Agreed:</u> The Note was never part of the suggested replacement. However, the text of the change was clarified.</td></tr>
<tr><td>12</td><td>James Maynard

Garmin (7)</td><td>1.9</td><td>The ADS-B Rebroadcast service is really a function of the TIS-B service. Therefore, the case for DF=18, CF=6 should be included in Table 2-15.</td><td><u>Table 2-15:</u> Determining TIS-B Message Type (DF=18, CF=2 to 6)
<table>
<tr><th>CF Field Value</th><th>TYPE Code (“ME” bits 6-8)</th><th>SUBTYPE Code (“ME” bits 6-8)</th><th>TIS-B Message Type</th></tr>
<tr><td rowspan="9">2 or 5</td><td>0</td><td>Not Present</td><td>TIS-B Fine Airborne or Fine Surface Position Message</td></tr>
<tr><td>1 - 4</td><td>Not Present</td><td>TIS-B Identification and Type Message</td></tr>
<tr><td>5 - 8</td><td>Not Present</td><td>TIS-B Fine Surface Position Message</td></tr>
<tr><td>9 - 18</td><td>Not Present</td><td>TIS-B Fine Airborne Position Message</td></tr>
<tr><td rowspan="3">19</td><td>0</td><td>Reserved</td></tr>
<tr><td>1 - 4</td><td>TIS-B Velocity Message</td></tr>
<tr><td>5 - 7</td><td>Reserved</td></tr>
<tr><td>20 - 22</td><td>Not Present</td><td>TIS-B Fine Airborne Position Message</td></tr>
<tr><td>23 - 31</td><td>Not Present</td><td>Reserved</td></tr>
<tr><td>3</td><td>Not Present</td><td>Not Present</td><td>TIS-B Coarse Airborne Position and Velocity Message</td></tr>
<tr><td>4</td><td>Not Present</td><td>Not Present</td><td>Reserved (for TIS-B Management Message)</td></tr>
<tr><td>6</td><td>0 to ~~22~~ 31</td><td>~~(As for CF = 2 or 5)~~
See Table 2-14</td><td>ADS-B Rebroadcast (see §2.2.18)</td></tr>
</table>
<u>WG-3 Agreed</u> to add the row to Table 2-15 as modified above.</td></tr>
</table>

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13	James Maynard Garmin (8)	1.14 (New)	In the DO-260A base document, §2.2.3.2.7.1.3.14 on "Capability Codes", the term "Operational Status of TCAS/ACAS systems/functions" is ambiguous. I believe this refers to TCAS II and not to TCAS I, and that for an aircraft equipped with TCAS I, bits 52 and 53 of the Target State and Status Message's "ME" field should be zero.	Add a Note before Table 2-56, as follows: ***Note:*** *Here "TCAS means "TCAS II or ACAS." For an aircraft equipped with TCAS I, "ME" bits 52 and 53 should both be ZERO.* **WG-3 Agreed and the proposed change will be made.**
14	James Maynard Garmin (9)	1.26	In §2.2.17.2.2 of DO-260A, the reference to Table 2-106 describes CF=2, 3, 4, or 5, but not CF=6.	In the first paragraph of §2.2.17.2.2, change the second sentence to read, "This field will be set to 2, 3, 4, 5, or 6 depending upon the TIS-B message as specified in Table 2-106." **WG-3 Rejected the proposed change because it would lead to confusion in the use of ADS-B Message formats for Rebroadcast.**
15	James Maynard Garmin (10)	1.31	**Editorial comment:** The ADS-B Rebroadcast service (ADS-R) is really a subset of the TIS-B service. It is not helpful to introduce the new term, "ADS-R." Just call it "ADS-B Rebroadcast" and describe it as a service provided by some TIS-B ground stations.	Modify the new §2.2.18 to describe the ADS-B Rebroadcast Service as a function of the TIS-B service. Eschew the term ADS-R, calling it ADS-B Rebroadcast instead. **After discussion, WG-3 agreed to make an entry into section 1.1 and Appendix B of DO-260A, via new changes, indicating the difference in TIS-B and ADS-R.**
16	James Maynard Garmin (11)	1.32	**Minor editorial comment:** In the first sentence of the changed Step 3, the expression "on the ground" should be hyphenated, as the three words are together used as an adjective modifying "status." Likewise, "transponder based" should be hyphenated, for the same reason.	Let the first sentence read as follows: "For **transponder-based** ADS-B transmitting systems that have automatic detection of **on-the-ground** status and have ground speed, airspeed or radio altitude available, the following procedure applies." (The highlighting of these changes with bold-face text should not be done in the actual Change 1 document.) **WG-3 Agreed: Edit made as suggested.**
17	James Maynard Garmin (12)	1.34	**Minor editorial comment:** The title of Table 2-124 should be consistent with the title of Step 3 of the measurement procedure.	In the table title and in the column headings, change "Vertical" to "Air/Ground" wherever it occurs. **WG-3 Agreed: Edit made as suggested.**

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18	James Maynard Garmin (13)	1.38	The text for §2.4.3.2.4.1.1, "Appropriate test procedures are provided in §2.4.3.2.4.1," should also be used to replace the existing text in §2.4.3.2.4.1.2.	Do so. **WG-3 Agreed: The change was edited to include §2.4.3.2.4.1.2.**
19	James Maynard & Kurt Schueler Garmin (14)	1.48	This change refers to §2.4.5.1.5.2 of the base document, DO-260A. My copy of DO-260A does not have this section! (It goes from §2.4.5.1.5 at the bottom of page 545 to §2.4.5.1.6 at the top of page 546.)	Change to "This change refers to §2.4.5.1.52…". **WG-3 Agreed: Edit made as suggested.**
20	James Maynard Garmin (15)	1.72 1.73	If the change called out in (1.72) is incorporated into (1.73), then there is no need for the change called out in (1.72)	Combine these two changes into one. **WG-3 Agreed: Edit made as suggested.**
21	James Maynard Garmin (16)	1.78	***Note 1*** is associated with subparagraph "1" but need not be deleted.	Retain Note 1 in §A.1.7.2. **WG-3 Agreed: The *Note* was never part of the suggested replacement. However, the text of the change was clarified.**
22	James Maynard Garmin (17)	1.89 (New)	In §A.1.7.7, titled "Globally Unambiguous Airborne Position Decoding, there is no need the time limit of 50 seconds between the "even" and "odd" format encoded surface position reports.	At the end of the first paragraph of §A.1.7.7., delete the words "and 50 seconds for surface formats". At the end of *Note 2* in §A.1.7.7., either delete the last two sentences, which read: "For targets on the airport surface, speeds are much less, and the transmission rate can be as low as one per 5 seconds. Therefore, the corresponding time limit for global decode is 50 seconds," or else, add, at the end of that *Note 2*, "(See §A.1.7.8.)" **WG-3 Agreed that the appropriate text should be moved to the appropriate section in the new section §A.1.7.8. Language was added to A.1.7.8 during the Teleconference on 5/16/06 to indicate when 50 seconds or 25 seconds was appropriate.**

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23	James Maynard Garmin (18)	1.102	According to the TIS-B MASPS, RTCA DO-286A, the ADS-B Rebroadcast Services is one of several TIS-B services. (It is the second TIS-B service to be defined, after the "TIS-B Fundamental Service." Accordingly, it is more proper to describe the message formats as additional TIS-B message formats rather than as formats of a new "ADS-R" service.	In the new §A.3.1, after the heading "A.3.1 Introduction," and before the *Notes*, insert an explanatory paragraph to read as follows: The TIS-B MASPS, RTCA DO-186A, defines, in addition to the "Fundamental ADS-B Service," an "ADS-B Rebroadcast Service" as an additional service that may be provided by the TIS-B service. The messages of the TIS-B Rebroadcast service are transmitted, not by aircraft, but by TIS-B ground stations. Also, change Note 2 in §A.3.1 to begin, "The ADS-B Rebroadcast Service complements the operation of ADS-B and of the TIS-B Fundamental Service by providing …." **WG-3 Agreed and the proposed change will be made.**
24	James Maynard Garmin (19)	New	I would prefer that the term "ADS-R" should not be used, as the ADS-B Rebroadcast service is one of the TIS-B services. However, if the term "ADS-R" should be retained, then a definition for it should be added to Appendix B of DO-260A with Change 1.	If the term "ADS-R" is retained, then add it to the list of acronyms in Appendix B, §B.1, defined as follows: ADS-R - ADS-B Rebroadcast (one of the TIS-B services) **After discussion, WG-3 agreed to make an entry into section 1.1 and Appendix B of DO-260A, via new changes, indicating the difference in TIS-B and ADS-R.**
25	James Maynard Garmin (20)	New	In Appendix B, §B.2, add a definition for the term "ADS-B Rebroadcast"	ADS-B Rebroadcast — One of the services provided by the TIS-B system: a TIS-B Service in which ~~TIS-B~~ ground stations rebroadcast on one data link (such as the 1090 MHz Extended Squitter data link described in these MOPS) ADS-B messages that were originally transmitted by aircraft or vehicles on another data link (such as the UAT, Universal Access Transceiver) ~~data link~~ described in the UAT MOPS, RTCA/DO-282A. **WG-3 Agreed to retain the term "ADS-R" and make the change as modified.**

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26	William Harman MIT Lincoln Lab	1.79	This change would add text to the material on CPR (the requirements material in Appendix A). When this proposal was being discussed by WG3, I recommended against adding it because this MOPS material is correct as it stands, and the proposed text does not add new information. Furthermore, the proposed new text would need some editorial review. WG3 decided to leave the proposal in the FRAC document, where the editorial review could be conducted. The word "expected" seems inappropriate to me. A possible alternative would be to replace " ... is not expected to change ... " with " ... does not change ... " Similarly the word "established" seems inappropriate to me. A possible alternative would be to replace "established" with "defined". There is also an editorial/technical problem with the words, " ... has actually been crossed ...". This wording tends to contradict the requirement (in A.1.7.3-d) that the NL function is never used except for the quantized values of latitude that are available to a receiver. In summary, I believe that this material would degrade rather than improve the MOPS.	Leave this MOPS material as it stands (without the proposed addition). **After discussion, it was agreed to leave the note as written.**

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27	William Harman MIT Lincoln Lab	1.79	While thinking about the issues raised by this proposed change, I've noticed an inconsistency in the corresponding test, and specifically in Table 2-130. This is the test to verify that the encoder correctly implements the NL calculation for the 58 transitions in each hemisphere. Of course the encoder is required to calculate NL using only the same information that will be available to a receiver (requirement is in A.1.7.3-d). But the test and Table 2-130 do not reflect this requirement.	Consider changing Table 2-130 to reflect the requirement in A.1.7.3-d. **After discussion, it was agreed that the resolution of Comment #28 would also satisfy this comment.**
28	Al Marshall Sensis Corp.	1.52, 1.57 1.59, 1.61 1.86, 1.89 1.91, & 1.93h	The **Non-Concur** comments of Sensis Corporation are reflected in the analysis and comments of **Attachment 1** to this document.	**After discussion, Sensis agreed to remove the Non-Concur associated with this comment. The resolution of this comment was to modify the text of the reasonableness test and to agree that a subgroup of WG-3 would work over the next few weeks to re-draft the test procedures that are associated with the revised reasonableness test. The Working Group rejected the modification of Table 2-130 as suggested in this comment.** **During the Teleconference on 5/16/06, the participants agreed to suggested changes for the reasonableness test and test procedures that are associated with it. The same text will be included in the 1090ES SARPs Technical Manual as agreed to by ICAO ASP WG-B during their meeting 8 – 12 May 2006 in Montreal.**

ATTACHMENT 1

Comments on proposed Change 1 to DO-260A, sections 1.52, 1.57, 1.59, 1.61, 1.86, 1.89, 1.91, 1.93h (NL selection in CPR decoding near transition latitudes).

Sensis **does not concur** with the reasonableness test and associated verification procedure added to CPR decoding. CPR Encoding transition latitude test inputs should be moved closer to the observable NL transition boundary to reduce the probability of encoding errors.

Summary

The proposed requirement for a reasonableness test of decoded position needs further consideration and may not be the best solution for the stated purpose ("to guard against the possibility that the decoder selects a different value of NL from the value that was used by the encoder"). If the CPR algorithms specified in Appendix A are followed, there will be no ambiguity in the selection of the number of longitude zones, NL. The ADS-B community would be better served by fixing the transition latitude test procedures to identify errant equipment. Further, the errors in choosing the wrong value of NL on encode or decode do not always yield an "unreasonable" position result that can be discovered by a test at the decoder. If the decoder is allowed (or required) to choose between two possible decoded positions, the utility of the position reporting system is reduced.

This issue was discussed in WG3 Meeting 20 where two examples were shown. The example position reports were decoded with 150 to 175 nautical miles of error. A brief reason for the error is that in the CPR technique, the longitude position is sent relative to a finite longitude zone shown in Figure 1. The fractional position within the zone is sent explicitly with 12 to 17 bits of resolution depending on report type, and the actual zone is computed indirectly by using a reference position. If the fractional position is encoded as though the target is in Zone A in the figure but the decoder determines it to be in Zone B, the error will be the offset of the western edges of the two zones. This has been observed to happen at latitudes very close to the transitions between zones, where different levels of precision and quantization can place the position in either zone. Fortunately, the CPR algorithm as specified does not leave any ambiguity. A parameter NL (number of longitude zones) is key to the determination of the correct zone. Step c of A.1.7.3. in DO-262A (page A-48 in volume 2) assures that the encoder uses the same value of NL that the decoder will determine, regardless of quantization.

Al Marshall – Sensis Corp

13 April 2006

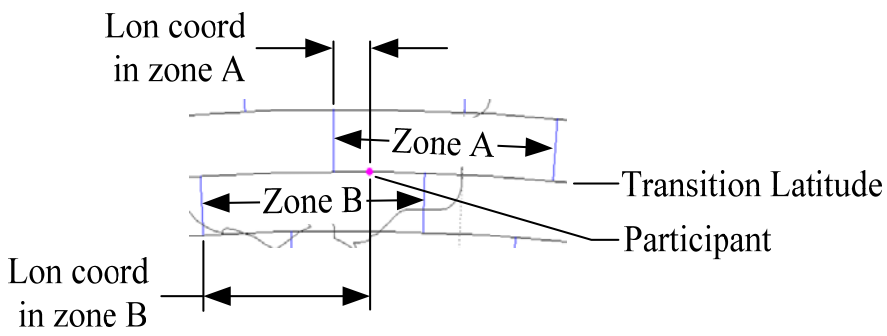


Figure 1 - Longitude Coordinate Variation with Longitude Zone

The rest of this report deals with several details of this issue.

1) Although the position errors observed in Australia were over 100 miles, errors in other parts of the world can be from a few meters on up. This makes the requirements, testing, and overall wisdom of a reasonableness test very complex. This is discussed in more detail.
2) A description of the CPR technique that contains helpful visualizations is offered. In this description, some of the subtleties that give rise to errors are pointed out.
3) Tests in DO-260A are intended to catch errors in encoding and decoding. Since these errors can happen arbitrarily close to the transition latitude, no test can be complete. A set of test values is suggested that use a standard quantization of 32-bit Angular Weighted Binary (a 9mm resolution). This represents a considerably tighter test than the current test tables and makes the likelihood of errors correspondingly smaller. Tests for units known to have greater internal precision from the position source can have appropriate test inputs generated, if deemed necessary.

Uncertainty associated with a reasonableness test

The discussion in WG3 Meeting 20 focused on two points in Australia at 36.850285934°S, 146.77314°E and 27.93897725768008°S, 153.0099722055288°E. The points are plotted in magenta in Figure 2 with NL transition latitudes (constant latitude black lines) and odd longitude zone boundaries (constant longitude blue lines)..

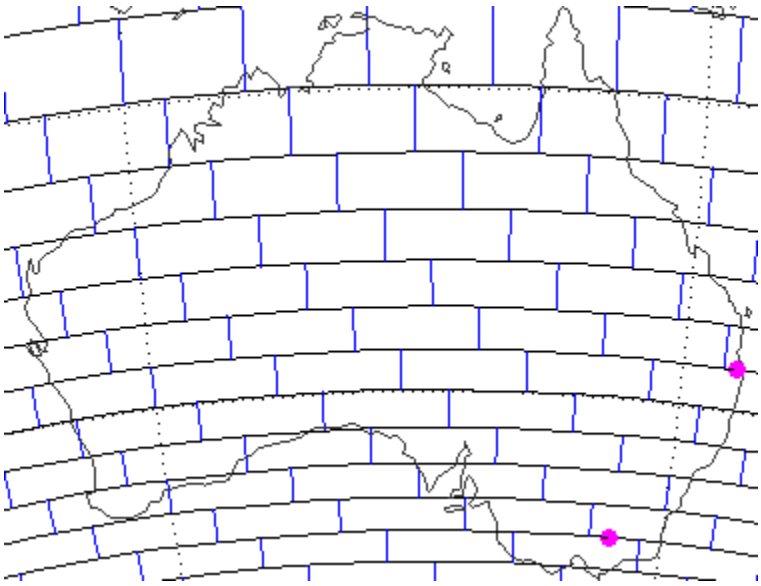


Figure 2 - Points of Reported ADS-B Position Error

The points are located in a region of the globe where substantial overlap of longitude zones along transition latitude boundaries exists. This overlap results in large differences in the encoded longitude if NL is selected incorrectly. Large differences in encoded longitude result in easily detectable longitude errors. At the points shown in Australia, the longitude error from locally unambiguous CPR decoding was approximately 150 nautical miles (NM) for the southern point and 175 NM for the eastern point.

Large overlaps of the longitude zones do not exist in all regions of the world. The overlap of the longitude zones becomes much smaller as longitude decreases. Figure 3 shows longitude zones near the Prime Meridian and 180° longitude. At the Prime Meridian, the encoding error resulting from incorrect selection of NL is exactly 0. As the longitude of the encoded point increases, the encoding error increases in increments of the encoding resolution (approx 5 meters for Nb=17 and approx 1.3 meters for Nb=19).

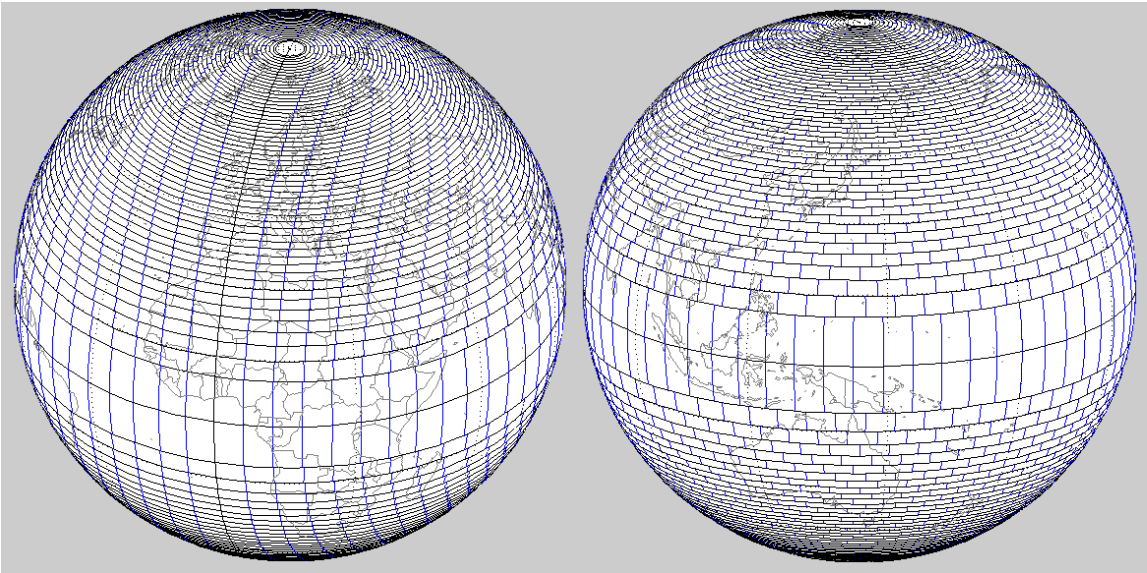


Figure 3 - CPR Longitude Zone Boundaries Near 0° Longitude (Left) and 180° Longitude (Right)

Detection and correction of NL-related errors on the order of a few tens of meters will have an element of uncertainty. The uncertainty will be greatest in areas near the prime meridian including Great Britain and France.

If a reasonableness test is added to DO-260A, the requirement must be much more explicit in the definition of "reasonable" than the text proposed in Change Notice 1. "Reasonable" will depend on the expected position and the containment radius when NL-related errors are comparable to containment radius. Verification procedures for the receiver's ability to discard or correct unreasonable position data must verify performance in the "harder" areas near the Prime Meridian.

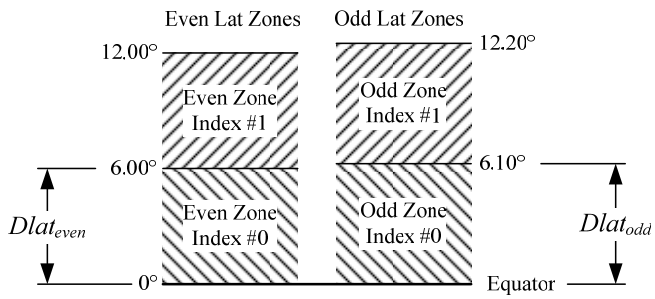
Limitations of the Current Transition Latitude Test

The transition latitude test procedure in DO-260A, section 2.4.3.2.4.7.1.1 [Table 2-130] is used to verify that the CPR encoder produces the correct latitude and longitude encodings near each of the NL transition latitudes. However, the input test latitudes are not as close as possible to the observable transition latitudes. The test leaves some uncertainty as to how the encoder will perform in the relatively large area between the test latitudes.

CPR Encoding Basics

A brief review of the author's possibly incorrect understanding of the CPR encoding algorithm will be presented as part of the rationale for the assertion above.

The CPR encoding process takes an input latitude and input longitude as real numbers and produces 2 integer coordinates YZ and XZ. The outputs represent the "Y-coordinate within the Zone" and "X-coordinate within the Zone." A "zone" is a range of latitude or longitude. Figure 3 depicts longitude zones (odd only). Figure 4 and Figure 5 show latitude zones.



$$Dlat_i = \frac{360°}{4 \cdot NZ - i}$$

$NZ = 15$
$i = 0$ for even encoding
$i = 1$ for odd encoding

Figure 4 - Definition of Latitude Zones

The encoding calculation uses two different zone sizes. "Even" latitude zones are exactly 6° vertically and "odd" latitude zones are approximately 6.10° vertically. Even and odd longitude zones have a similar relationship. One half of the position reports sent by a participant use even format and the other half use odd. The even and odd formats are required for CPR decoding. Figure 5 shows even and odd latitude zone boundaries plotted on the globe.

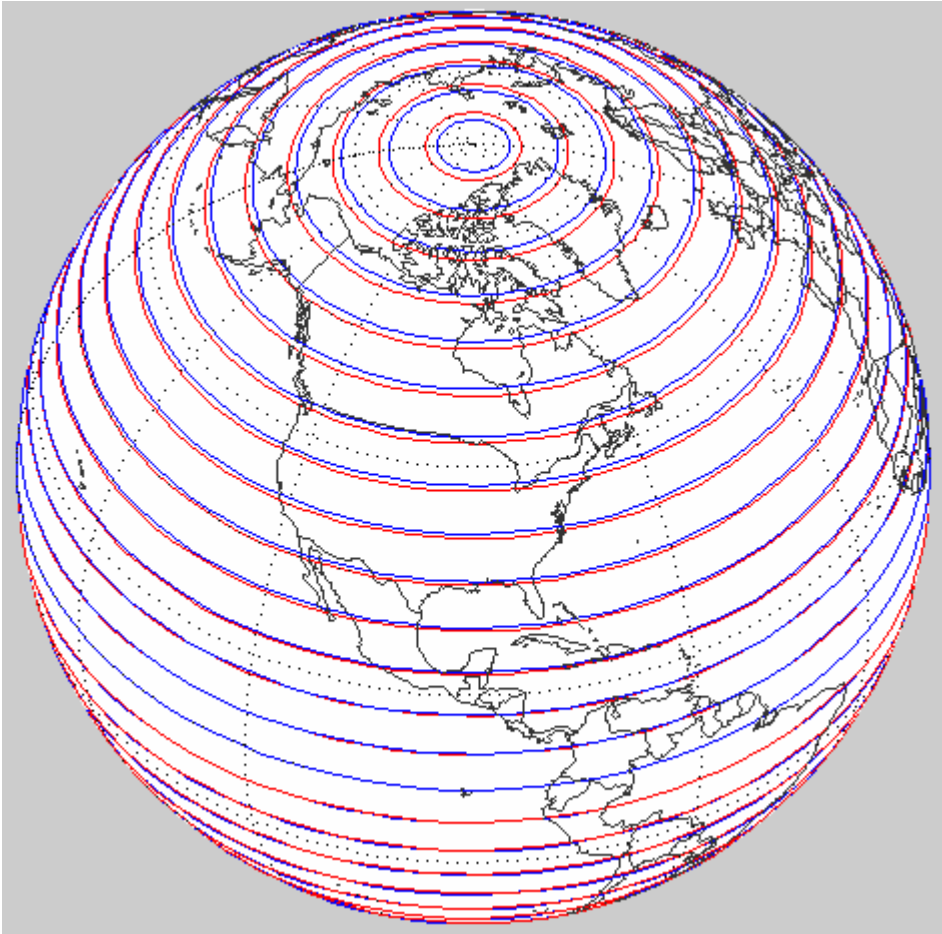


Figure 5 - Latitude Zone Boundaries (Red = Even, Blue = Odd)

Each zone is comprised of bins. The number bins in each zone is fixed depending on the type of position being conveyed. For airborne position, the number is 2^{17} or 131072. For surface position, the number is 2^{19} or 524,288. Each latitude bin is identified by the coordinate YZ. YZ is the bin number relative to the southern edge of the latitude zone (even in the southern hemisphere). The CPR decoding algorithms produce a latitude value (a real number) from YZ which is the centerline of the bin. The relationship between latitude zones and bins is shown in Figure 6.

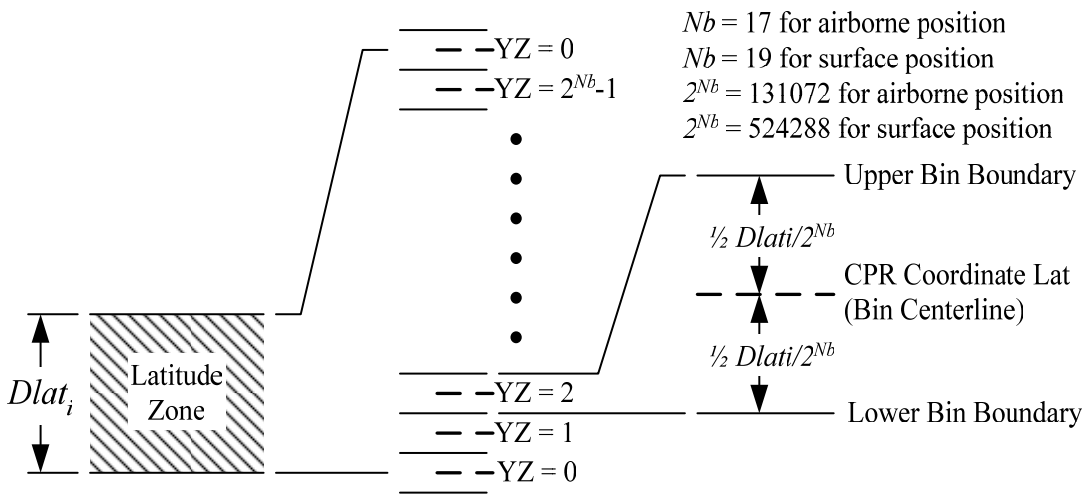


Figure 6 - Latitude Zones and Bins

The CPR algorithm maintains approximately constant distance resolution all over the globe. The resolution is equal to the bin size and is directly proportional to the zone size. The bin size is approximately 5 meters for airborne encoding and 1.3 meters for surface encoding. Latitude zones are approximately 360 miles tall and longitude zones are approximately 360 miles wide. In order to maintain constant longitude zone widths at all latitudes (i.e., miles or km in the east-west direction), the number of longitude zones decreases when moving from the equator to the poles. The equation for the number of longitude zones (NL) as a function of latitude is specified in A.1.7.2.d of DO-260A:

$$\mathrm{NL}(lat) = \mathrm{floor}\left(2\pi \cdot \left[\arccos\left(1 - \frac{1-\cos\left(\frac{\pi}{2\cdot NZ}\right)}{\cos^2\left(\frac{\pi}{180^\circ}\cdot|lat|\right)}\right)\right]^{-1}\right) \qquad \text{Eq 1 [A.1.7.2.d]}$$

A rearranged version of Eq 1 gives transition latitudes as a function of the number of longitude zones [A1.7.2.d note 5]:

$$lat = \frac{180°}{\pi} \cdot \arccos\left(\sqrt{\frac{1-\cos\left(\frac{\pi}{2 \cdot NZ}\right)}{1-\cos\left(\frac{2\pi}{NL}\right)}}\right) \text{ for } NL = 2 \text{ to } 4 \cdot NZ - 1, \qquad \text{Eq 2 [A1.7.2.d]}$$

The longitude coordinate XZ has the same meaning as YZ except that it represents the bin number measured from the *west* edge of the zone instead of the south edge. The longitude angular zone width, $Dlon_i$ (in degrees of longitude) depends on the value of NL and is given by the equation in section A.1.7.3.d:

$$Dlon_i = \begin{cases} \frac{360°}{\mathrm{NL}(Rlat_i) - i}, & \text{when } \mathrm{NL}(Rlat_i) - i > 0 \\ 360°, & \text{when } \mathrm{NL}(Rlat_i) - i = 0 \end{cases} \qquad \text{Eq 3 [A.1.7.3.d]}$$

$Rlat_i$ will be discussed shortly. A visual representation of these equations is shown in Figure 7. Red lines are even longitude zone boundaries and blue lines are odd longitude zone boundaries. Lines of constant latitude are the transition latitudes defined by Equation 2.

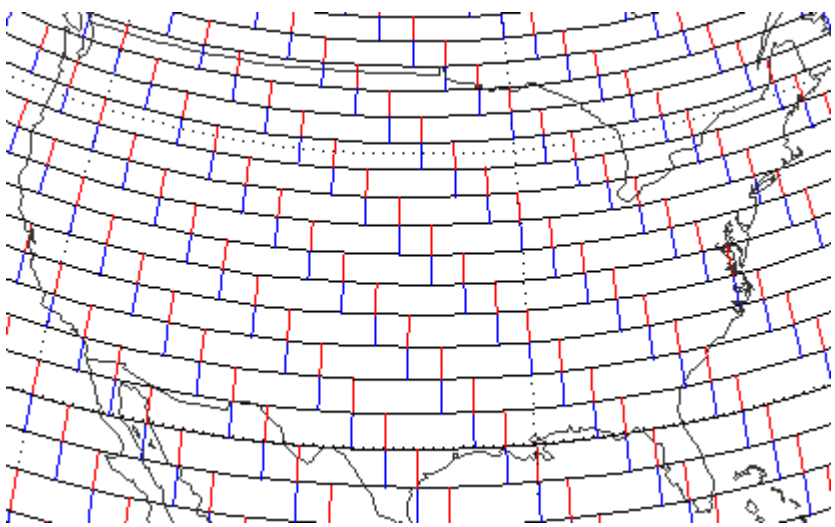


Figure 7 - Even and Odd Longitude Zones With Transition Latitudes

Note in Figure 7 that the location of the western zone boundary for a given encoding format (i.e., even or odd) changes on either side of a transition latitude. If the distance from the western zone boundary to a particular longitude is measured from the wrong zone boundary, XZ will be incorrect. Figure 8 is an example of such a case.

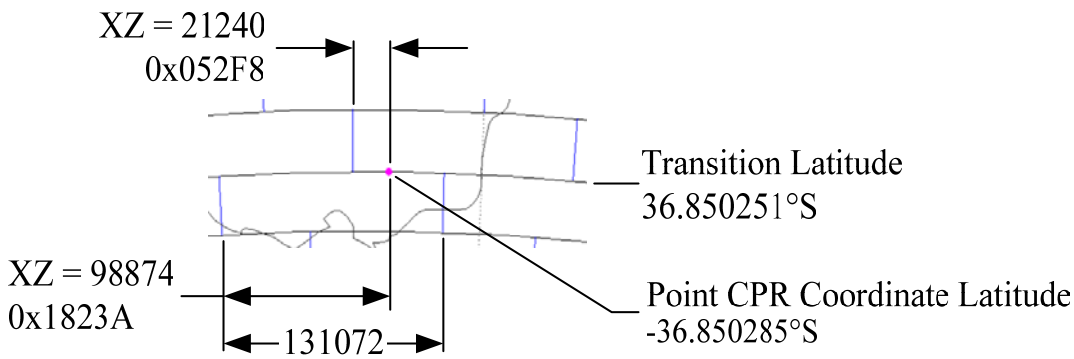


Figure 8 - Longitude Encoding Example

The CPR coordinate latitude of the point in Figure 8 is below the transition latitude. The encoder should have determined XZ using the western zone boundary in the lower zone. This would have resulted in a value of 98874 for XZ. However, the encoder incorrectly determined XZ from the western boundary of the upper zone resulting in a value of 21240 for XZ.

Encoding Steps

The first step of the encoding process is to determine the latitude zone size $Dlat_i$. $Dlat_i$ is calculated with the equation in Figure 4 which comes from Section A.1.7.3.a of DO-260A.

The second step of the encoding process converts the input latitude into an output latitude coordinate YZ_i. The input latitude can be any real number that can be represented by a digital computer. YZ_i is limited to a finite set of integers (0 to 131072) which represent discrete latitudes (CPR Coordinate Latitudes). Equation 4 converts an input latitude into a YZ_i value for an airborne participant.

$$YZ_i = \text{floor}\left(2^{17} \cdot \frac{\text{MOD}(lat, Dlat_i)}{Dlat_i} + \frac{1}{2}\right) \qquad \text{Eq 4 [A.1.7.3.b]}$$

The modulus function returns the number of degrees from the southern edge of the zone to the input latitude. Dividing this by the latitude zone size $Dlat_i$ produces the "fraction into the zone" of the input latitude. The product of the "fraction into the zone" and the number of bins in the zone (i.e., 2^{17}) is the bin number of the input latitude. The product is not necessarily an integer so it is rounded to the nearest integer by adding ½ and taking the floor of the sum. The formula for surface encoding is the same except that the number of bins in the zone is 2^{19}.

The third step in the encoding process is to recover the CPR coordinate latitude of YZ_i. Because Equation 4 performs rounding, the coordinate latitude represented by YZ_i will not equal the input latitude in most cases.

$$Rlat_i = Dlat_i \cdot \left(\frac{YZ_i}{2^{17}} + \text{floor}\left(\frac{lat}{Dlat_i} \right) \right)$$ Eq 5 [A.1.7.3.c]

$YZ_i / 2^{17}$ is the "fraction into the zone" of the latitude bin indexed by YZ_i. Floor($lat/Dlat_i$) is the zone index number. The first latitude zone north of the equator is index number 0. The sum of the terms inside the parentheses is the number of whole zones plus the fraction into the last zone of YZ_i. The product of this and $Dlat_i$, the number of degrees per zone, is the CPR coordinate latitude of YZ_i.

In the fourth step, $Rlat_i$ from equation 5 is used to determine NL from Equation 1 or from a lookup table based on equation 2. Then, $Dlon_i$ is calculated with Equation 3. Using $Rlat_i$ in the determination of NL ensures that the transmitted value of YZ is consistent with the value of NL used for longitude encoding. The step also ensures that only one value of NL is used for any latitude within a single latitude bin. The receiver only knows the latitude that is recovered from YZ and must determine NL based on this value. If more than one value of NL was used for latitudes in the same bin, the receiver would have no reliable way to determine which value of NL was appropriate.

The next step is to encode the longitude. This is done with Equation 6.

$$XZ_i = \text{floor}\left(2^{17} \cdot \frac{\text{MOD}(lon, Dlon_i)}{Dlon_i} + \frac{1}{2} \right)$$ Eq 6 [A.1.7.3.e]

Equation 6 works in the same manner as Equation 4 except that the inputs and results are longitude values.

The final step takes the least significant 17 bits of YZ_i and XZ_i. For surface position, this fits a 19 bit number into a 17 bit space but reduces the unambiguous range from 360 to 90 miles. This step is not relevant to transition latitude testing and will not be discussed further.

Testing of CPR Encoding

For each NL transition latitude, a lower and upper test latitude are specified (see Table 2-130 in DO-260A). The input test latitudes are the nearest even surface CPR coordinate latitudes above and below the transition latitude. The input longitude is 45°E for all tests. A segment of Table 2-130 is shown in Figure 9.

Table 2-130: Verification of Transition Table

Latitude in degrees (rounded to nearest AWB value)				Even Surface Position Encodings			
lat_{low}	lat_{low}	lat_{up}	lat_{up}	lower		upper	
Decimal	HEX	Decimal	HEX	latitude	longitude	latitude	longitude
10.470463	077216EF	10.470474	07721777	1F5EB	10000	1F5EC	00000
14.828167	0A8B62AB	14.828178	0A8B6333	1C559	00000	1C55A	10000
18.186253	0CEEB4CD	18.186264	0CEEB555	03F93	10000	03F94	00000
21.029388	0EF44889	21.029400	0EF44911	00A08	00000	00A09	10000
23.545040	10BE3E66	23.545052	10BE3EEF	164B5	10000	164B6	00000
25.829247	125E1222	25.829258	125E12AB	07062	00000	07063	10000
27.938976	13DE22AB	27.938988	13DE2333	14081	10000	14082	00000
29.911354	15453222	29.911366	154532AB	1E1BE	00000	1E1BF	10000
31.772095	1697EEEF	31.772106	1697EF77	05CE0	10000	05CE1	00000
33.539932	17D9C222	33.539944	17D9C2AB	0B84C	00000	0B84D	10000
35.228989	190D3DDE	35.229000	190D3E66	0F8D4	10000	0F8D5	00000
36.850250	1A346222	36.850262	1A3462AB	12238	00000	12239	10000

Figure 9 - DO-260A Transition Latitude Test Inputs and Expected Outputs

An example will be examined using the last line of Figure 9. The last line tests the transition latitude between NL = 47 and NL = 48. The even CPR surface position encodings nearest this transition latitude are 12238 (hex) and 12239 (hex). The difference between these values is 1 bin width or approximately 1.3 meters, the smallest difference that can be expressed by even CPR surface encoding. The 32 bit Angular Weighted Binary (AWB)[1] hex lat_{low} and lat_{up} values in columns 2 and 4 are 1A346222 and 1A3462AB. The difference between these values (i.e., the number of unique AWB input values between them) is 89 (hex) or 137 (decimal). The AWB values for lat_{low} and lat_{up} are the closest AWB representation of the CPR coordinate latitudes for the coordinates in columns 5 and 7. These latitudes are depicted in Figure 10.

Careful examination of Figure 10 and the behavior of Equations 1 through 6 reveals an interesting subtlety. NL should change when the input latitude crosses the CPR bin boundary. The bin boundary is not coincident with the transition latitude produced by Equation 2. NL changing at the bin boundary is a consequence of basing the NL lookup on $Rlat_i$ (as opposed to *lat*, the input latitude) in equation 3. The input latitude is rounded to the CPR coordinate latitude by Equation 4. The CPR coordinate latitude $Rlat_i$ is recovered by Equation 5 and is used in Equation 3 to get NL, and ultimately, $Dlon_i$.

[1] Angular Weighted Binary encoding is a number between 0 and 2^{32}-1 inclusive. Each increment represents $360/2^{32}$ degrees in either latitude or longitude. 1 AWB latitude increment represents approximately 9.3 mm (0.36 inches) on the earth's ellipsoid. Latitude encodings start at 0 at the equator and increase toward the north pole. The series continues around the globe until the equator is reached again. Latitude encodings between 90 and 270 degrees exclusive are not meaningful in this discussion.

Trans Lat Dbl Prec
36.85025107593480 1A34622C
36.85025107593480
Trans Lat AWB
36.85025107115500 1A34622C
36.85025107115500
Rlat even low Dbl Prec
36.85025024414060 1A346222
36.85025024414060 CPR 12238 (hex)
Rlat even high Dbl Prec
36.85026168823240 1A3462AB
36.85026168823240 CPR 12239 (hex)
Rlat odd low Dbl Prec
36.85025102001130 1A34622B
36.85025102001130 CPR 05095 (hex)
Rlat odd high Dbl Prec
36.85026265807070 1A3462B6
36.85026265807070 CPR 05096 (hex)
Even bin boundary lat Dbl Prec
36.85025596618650 1A346266
36.85025596618650
Odd bin boundary lat Dbl Prec
36.85025683904100 1A346271
36.85025683904100
Even Test Lat Low Dbl Prec
36.85025593265890 1A346266
36.85025593265890
Even Test Lat High Dbl Prec
36.85025601647790 1A346267
36.85025601647790
Odd Test Lat Low Dbl Prec
36.85025677084920 1A346270
36.85025677084920
Odd Test Lat High Dbl Prec
36.85025685466820 1A346271
36.85025685466820

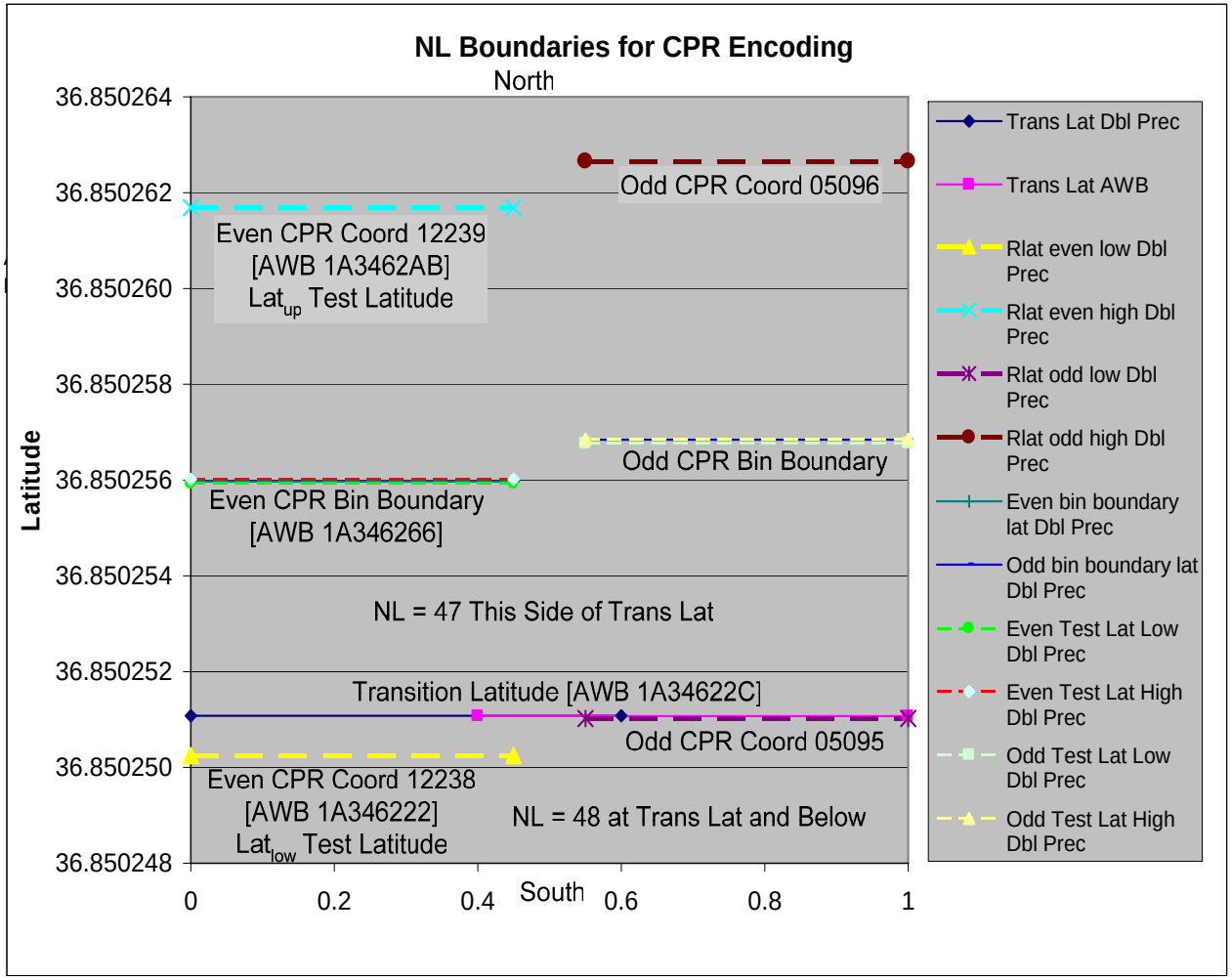


Figure 10 - Important Latitudes at the Transition Boundary Between NL = 48 and NL = 47 in the Northern Hemisphers

The test latitudes in DO-260A, Table 2-130 should be adjusted to straddle the closest bin boundary to each transition latitude. This will verify that encoders implement correct NL determination based on $Rlat_i$. The test latitudes should be separated by 1 AWB increment. Figure 11 depicts the tightening of test latitudes for the example shown in Figure 10.

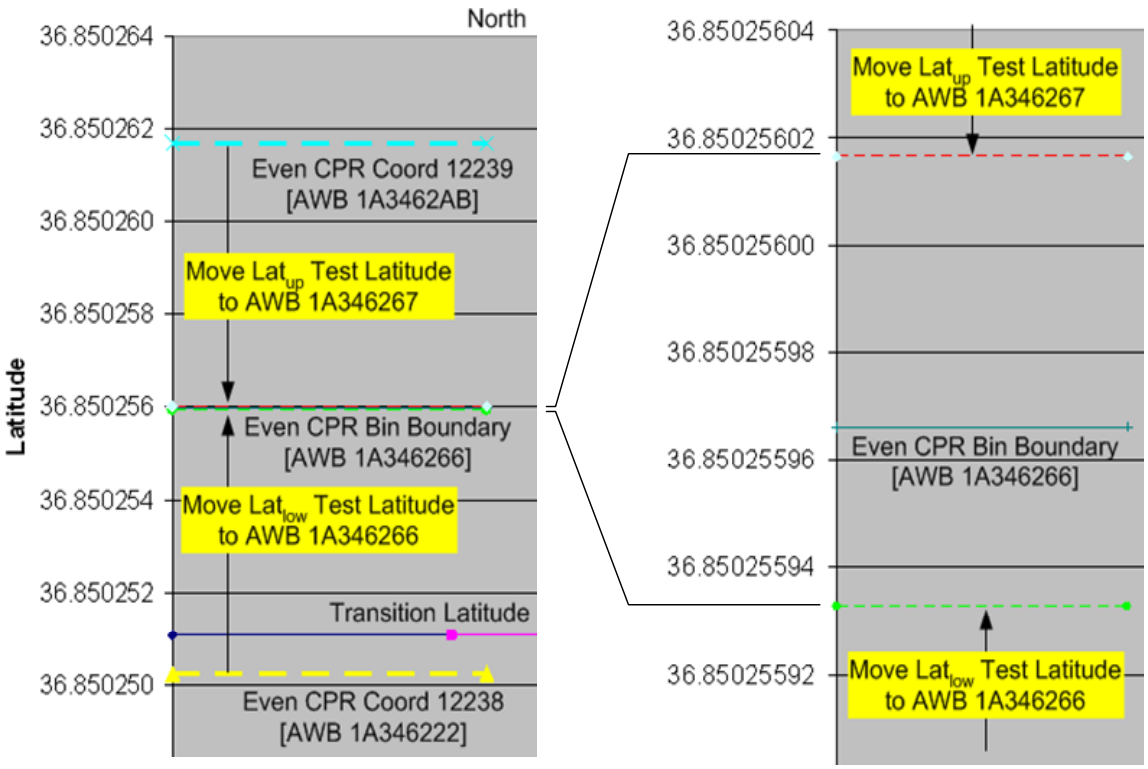


Figure 11 - Adjustment of Test Latitudes to Straddle Bin Boundaries

Table 1 is a revised version of Table 2-130 with the input latitudes changed as described in the preceding paragraphs.

Table 1 - Inputs and Expected Outputs for the CPR Transition Latitude Encoding Test

Input Latitude In Degrees				Expected Even Surface Position Encodings			
Lat-low		Lat-up		lower		upper	
Decimal	AWB	Decimal	AWB	lat	long	lat	long
10.4704685044	07721733	10.4704685882	07721734	1F5EB	10000	1F5EC	00000
14.8281726055	0A8B62EE	14.8281726893	0A8B62EF	1C559	00000	1C55A	10000
18.1862583105	0CEEB511	18.1862583943	0CEEB512	03F93	10000	03F94	00000
21.0293940827	0EF448CC	21.0293941665	0EF448CD	00A08	00000	00A09	10000
23.5450457968	10BE3EAA	23.5450458806	10BE3EAB	164B5	10000	164B6	00000
25.8292522095	125E1266	25.8292522933	125E1267	07062	00000	07063	10000
27.9389819317	13DE22EE	27.9389820155	13DE22EF	14081	10000	14082	00000
29.9113597535	15453266	29.9113598373	15453267	1E1BE	00000	1E1BF	10000

Input Latitude In Degrees				Expected Even Surface Position Encodings			
Lat-low		Lat-up		lower		upper	
Decimal	AWB	Decimal	AWB	lat	long	lat	long
31.7721004318	1697EF33	31.7721005157	1697EF34	05CE0	10000	05CE1	00000
33.5399379395	17D9C266	33.5399380233	17D9C267	0B84C	00000	0B84D	10000
35.2289943583	190D3E22	35.2289944421	190D3E23	0F8D4	10000	0F8D5	00000
36.8502559327	1A346266	36.8502560165	1A346267	12238	00000	12239	10000
38.4124202281	1B50C488	38.4124203119	1B50C489	13770	10000	13771	00000
39.9225711264	1C63AEAA	39.9225712102	1C63AEAB	13AE7	00000	13AE8	10000
41.3865222316	1D6E2FBB	41.3865223154	1D6E2FBC	12E99	10000	12E9A	00000
42.8091373108	1E712A66	42.8091373947	1E712A67	1142F	00000	11430	10000
44.1945476364	1F6D5F33	44.1945477203	1F6D5F34	0ED12	10000	0ED13	00000
45.5462664831	206371DD	45.5462665670	206371DE	0BA75	00000	0BA76	10000
46.8673381582	2153F044	46.8673382420	2153F045	07D62	10000	07D63	00000
48.1603946630	223F5511	48.1603947468	223F5512	036BF	00000	036C0	10000
49.4277591258	23260C88	49.4277592096	23260C89	1E757	10000	1E758	00000
50.6715030503	24087733	50.6715031341	24087734	18FDF	00000	18FE0	10000
51.8934230134	24E6E8CC	51.8934230972	24E6E8CD	130F4	10000	130F5	00000
53.0951671489	25C1AE22	53.0951672327	25C1AE23	0CB26	00000	0CB27	10000
54.2781772278	26990A66	54.2781773116	26990A67	05EF3	10000	05EF4	00000
55.4437808599	276D3B77	55.4437809438	276D3B78	1ECCF	00000	1ECD0	10000
56.5931910742	283E79DD	56.5931911580	283E79DE	17524	10000	17525	00000
57.7274722885	290CF733	57.7274723724	290CF734	0F84F	00000	0F850	10000
58.8476428203	29D8E2EE	58.8476429041	29D8E2EF	076A9	10000	076AA	00000
59.9545955099	2AA266AA	59.9545955937	2AA266AB	1F080	00000	1F081	10000
61.0491770972	2B69A9DD	61.0491771810	2B69A9DE	1661E	10000	1661F	00000
62.1321658418	2C2ED0CC	62.1321659256	2C2ED0CD	0D7C7	00000	0D7C8	10000
63.2042712718	2CF1FC88	63.2042713556	2CF1FC89	045B9	10000	045BA	00000
64.2661685497	2DB34C88	64.2661686335	2DB34C89	1B02F	00000	1B030	10000
65.3184527904	2E72DC88	65.3184528742	2E72DC89	1175D	10000	1175E	00000
66.3617076259	2F30C7BB	66.3617077097	2F30C7BC	07B76	00000	07B77	10000
67.3964710068	2FED2733	67.3964710906	2FED2734	1DCA9	10000	1DCAA	00000
68.4232234675	30A81155	68.4232235514	30A81156	13B20	00000	13B21	10000
69.4424228277	31619B77	69.4424229115	31619B78	09703	10000	09704	00000
70.4545154236	3219DA66	70.4545155074	3219DA67	1F079	00000	1F07A	10000
71.4598674607	32D0DF33	71.4598675445	32D0DF34	147A2	10000	147A3	00000
72.4588450603	3386BAEE	72.4588451441	3386BAEF	09C9E	00000	09C9F	10000
73.4517688304	343B7C88	73.4517689142	343B7C89	1EF89	10000	1EF8A	00000
74.4389361609	34EF31DD	74.4389362447	34EF31DE	1407D	00000	1407E	10000
75.4205646459	35A1E511	75.4205647297	35A1E512	08F8D	10000	08F8E	00000
76.3968486618	36539F33	76.3968487456	36539F34	1DCCA	00000	1DCCB	10000
77.3678913061	37046511	77.3678913899	37046512	1283D	10000	1283E	00000
78.3337382600	37B438CC	78.3337383438	37B438CD	071EA	00000	071EB	10000
79.2942866776	38631599	79.2942867614	3863159A	1B9C8	10000	1B9C9	00000

Input Latitude In Degrees				Expected Even Surface Position Encodings			
Lat-low		Lat-up		lower		upper	
Decimal	AWB	Decimal	AWB	lat	long	lat	long
80.2492275182	3910ED11	80.2492276020	3910ED12	0FFBC	00000	0FFBD	10000
81.1980113480	39BDA599	81.1980114318	39BDA59A	04396	10000	04397	00000
82.1395740006	3A690D99	82.1395740844	3A690D9A	184F9	00000	184FA	10000
83.0719928350	3B12CB77	83.0719929188	3B12CB78	0C33D	10000	0C33E	00000
83.9917316101	3BBA3A66	83.9917316940	3BBA3A67	1FD2D	00000	1FD2E	10000
84.8916606791	3C5E0E22	84.8916607630	3C5E0E23	1305A	10000	1305B	00000
85.7554148789	3CFB4BFF	85.7554149628	3CFB4C00	0572E	00000	0572F	10000
86.5353755280	3D8948CC	86.5353756119	3D8948CD	16168	10000	16169	00000
87.0000057109	3DDDDE22	87.0000057947	3DDDDE23	00000	00000	00001	10000

Table 1 has the same expected output encodings as Table 2-130 in DO-260A but the input latitudes have been tightened to the two closest 32 bit AWB latitudes that straddle the CPR latitude bin boundary. Since the test latitudes are separated by approximately 9 mm, there could be some uncertainty about the behavior of encoders that accept inputs with finer resolution than 32 bit AWB (i.e., resolution finer than 9.3 mm). Such encoders should be tested with the closest possible input values above and below the bin boundary.