DRAFT APPENDIX A

PROVISIONING FOR POTENTIAL WAKE VORTEX AND ARRIVAL MANAGEMENT ADS-B APPLICATIONS

This Page Intentionally Left Blank

APPENDIX A PROVISIONING FOR POTENTIAL WAKE VORTEX AND ARRIVAL MANAGEMENT ADS-B APPLICATIONS

A.1 Introduction

This Appendix discusses the potential 1090 Extended Squitter (ES) broadcast of Meteorological (MET) data and Air-Reference Vector (ARV) data for potential next generation ADS-B applications such as wake vortex based separation procedures and implementation of next generation arrival management systems. These applications are anticipated to provide capacity benefits, enhanced safety, and efficiency through future ground-based and airborne solutions. This section provides justification for introducing such broadcast data into a future 1090ES MOPS. Later sections provide initial estimates of desired data elements, update rates, and signal provisioning for future versions of 1090ES MOPS. This informative appendix to DO 260B/ED-102A is intended to facilitate the investigation of a range of applications enabled by the proposed data broadcasts, with the goals of (1) advising aircraft operators on how they can provision their aircraft at present to support these potential ADS-B applications and (2) laying the groundwork for international agreement on the inclusion of support for these applications in a future revision of these MOPS.

The Mode S 1090 MHz extended squitter capability was designed to provide an efficient framework for message transfer for air-to-ground, air-to-air, and ground-to-air communications [ICAO doc 9871 & RTCA doc]. The use of aircraft conducting routine operations as real-time sources of weather data via data link was among the envisioned uses of the 1090ES. This appendix describes two specific potential meteorological message formats for 1090ES and the transmission rates desired to enable emerging wake vortex and arrival management applications. However, the message content and data transmissions rates developed for these specific applications are further envisaged to support a variety of additional NextGen applications. Moreover, the message content, message transmission rates, and supporting infrastructure described in this appendix are targeted to support far-term airborne applications to provide real-time onboard wake turbulence avoidance information to flight crews.

Wake turbulence constraints have been identified as a major contributing factor to inefficient use of the Nation's airspace capacity, especially when Instrument Flight Rules (IFR) operations are in effect [NRC decadal study]. Concept exploration research by NASA and FAA has indicated that greater utilization of the nation's airspace could be accomplished if the location of wake turbulence from aircraft could be known with sufficient fidelity to allow following aircraft to fly paths that are free of hazardous turbulence. Significant potential increases in airport capacity, as much as a 40% increase at several airports during some periods of IMC, are achievable.

Mid-term wake avoidance solutions will most likely employ ground-based systems to receive and process down-linked meteorological and aircraft data potentially provided by ADS-B. This data will be integrated with flight plan and National Airspace Systems (NAS) data received through ground networks. Ground-based processors will compute wake safe 4D trajectories for individual aircraft and recommend traffic flow management options for arrival and departure operations. This data will become inputs to decision support tools (DSTs) for controllers and traffic flow management to optimize NAS operations. As envisioned by NextGen and SESAR concepts of operation, individual 4D wake-safe trajectories will be communicated to appropriate flight crews to provide a high level of shared situational awareness.

NextGen and SESAR concepts for arrival management and associated trajectory synthesis functions are also critically dependent on more real-time aircraft data. Specific data elements are needed to enhance reliability of medium term (~ 40 minute) prediction of aircraft trajectories during the descent and arrival phase of flight, for scheduling the arrival of successive aircraft at critical entry points into the terminal area, and to the final approach fix of congested runways. These include real-time winds aloft and aircraft weight data. The envisioned concepts include both ground based and air-to-air applications of broadcast MET and ARV data.

A.1.1 Proposed Wake Turbulence Applications

The FAA Wake Turbulence Program has proposed initial ground-based wake turbulence avoidance applications that require the availability of near real-time meteorological data that is not available from current sensors. These applications will determine wake-free trajectories for aircraft based on analysis of meteorological data and calculation of the resulting movement of hazardous wakes. These initial applications will be based on the lateral transport of wakes by crosswind and will not rely on any wake decay mechanisms to ensure safety. Wake-free trajectory information will be an input to ground-based ATM automation that allows ATC to separate aircraft from hazardous wakes while meeting other trajectory constraints.

Wake avoidance applications planned for the mid-term and far-term will require near real-time atmospheric profile information in order to accurately determine the spatial extent of a wake hazard. ADS-B equipped aircraft, with appropriate provisioning, have the potential to measure and report meteorological data at a high resolution, under all weather conditions, and over regions of operational interest.

The temporal and spatial scales of hazardous aircraft wake turbulence are dependent on ambient atmospheric conditions. Highly turbulent atmospheres can result in wakes decaying more quickly, sometimes in as little as 40-60 seconds. Stable atmospheric conditions promote longer wake lifetimes wherein heavy aircraft may generate hazardous wake turbulence that persists for more than two minutes. This difference in wake lifetime can strongly influence the spatial aspect of the wake hazard based on phase of flight and typical aircraft speeds. If a wake decays in 60 seconds or 120 seconds, this uncertainty can result in a hazardous wake area 2-4 miles long at typical final approach speeds or 8-16 miles long at en route cruise speeds. There are two aspects of wake turbulence that are important for wake avoidance, the location and strength of the wake. Ambient atmospheric conditions critically impact wake vortex lifetimes and affect their strength at any specific instant. The wake strength, in turn, is a primary consideration in how quickly wakes descend below the flight path of the generating aircraft.

Two mid-term applications based on potential ADS-B OUT capabilities are under development:

1. The wake turbulence mitigation for arrivals system (WTMA-S) provides additional capacity at airports with closely spaced parallel runways (CSPR)[1]

[1] Closely spaced parallel runways are defined here as parallel runways with centerlines separated by 2500 feet or less.

when instrument flight rules are being applied. The WTMA-S predicts operationally significant periods of time when stable crosswinds permit reduced separations between pairs of aircraft arriving on the two parallel runways. Crosswinds along the arrival flight path transport the wake turbulence generated by a lead aircraft out of the flight path of a following aircraft. WTMA-S complements the recently enacted FAA Order 7110.308 by enabling heavy aircraft and Boeing-757 aircraft to participate in a CSPR arrival procedure as lead aircraft and by enabling reduced wake turbulence separations at additional airports. WTMA-S utilizes the meteorological data that potentially could be transmitted from aircraft via ADS-B as input to the crosswind prediction algorithm and as part of a real-time monitoring function to ensure safety.

2. Crosswind-based reductions in en route separations are envisioned for more efficient flight operations. This application would utilize meteorological data transmitted from aircraft to enable safe reductions in en route separations controllers must apply for wake turbulence when aircraft climb or descend through the altitude of a proximate aircraft and when faster aircraft overtake a slower aircraft. Currently, controllers must maintain a minimum separation of 5 NM between co-altitude aircraft or 1000 foot vertical separations to protect against potential collisions and wake turbulence encounters. However, much smaller lateral separations can potentially provide avoidance of wake turbulence when the flight path of the maneuvering aircraft is offset. The en route wake avoidance application will use meteorological data transmitted from aircraft potentially via ADS-B to generate wake-free trajectories for maneuvering aircraft. It will be integrated with emerging ADS-B surveillance capabilities to enable an overall reduction in en route separations. Smaller deviations to preferred flight paths will be required, resulting in savings in time, fuel burned, and emissions.

A high level system diagram of these applications is shown in Figure A-1, assuming that the potential use of ADS-B becomes a reality. A processor in the aircraft will obtain required meteorological data from on-board sensors and computer systems and format this data for transmission via ADS-B. These data will be broadcast by ADS-B in the formats and at the frequencies described in section A.3. Ground receivers will provide these data to an ADS-B ground processor, which will parse the data messages and provide required data elements to a ground-based wake processor. The meteorological data algorithm in this processor will construct atmospheric profiles based on data provided by aircraft via ADS-B and other meteorological data available via ground data networks. A 4-D wake-free trajectory will be determined for each aircraft and provided to a trajectory processor. These trajectories will be processed and provided to ATC ground automation for use in ATC separation functions.

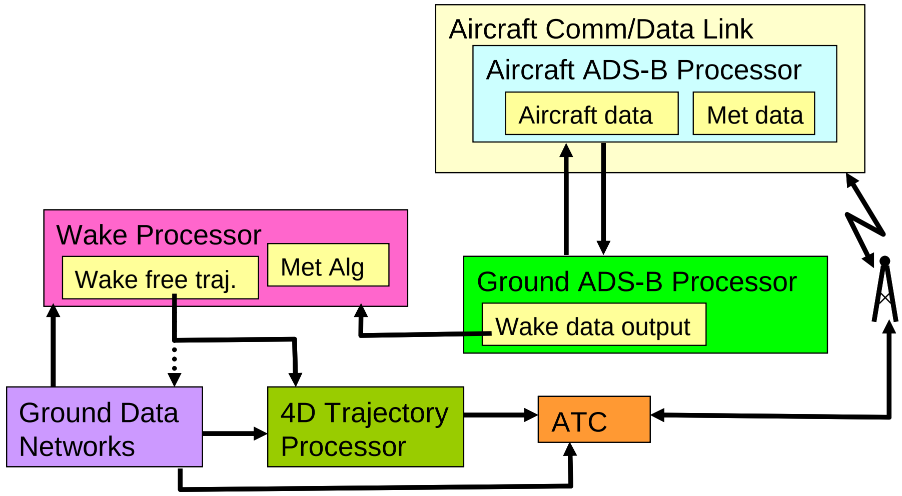

Figure A-1 System Diagram for Initial and Mid-Term Ground-Based Wake Applications Using ADS-B

This is a first step in the development of a series of potential ADS-B supported wake avoidance applications that will enable transition to far-term NextGen and SESAR operational concepts. Subsequent enhancements to the initial applications may also include the consideration of wake decay and sink in computing wake-free trajectories. Follow-on ground-based applications can use the same data elements recommended in this proposal to enable additional wake avoidance capabilities.

The initial applications being proposed have a high potential to produce early benefits for users. There are, however, multiple wake capabilities planned for the mid and far-term that can leverage better knowledge of winds. The Wake Turbulence Mitigation for Departures (WTMD) is one such capability. It is currently being developed for implementation in the 2012-2014 timeframe. WTMD is a wind-based departure capability that relies on the accurate forecast of periods when winds will not allow wakes to drift between the departure path of Heavy aircraft and that of another aircraft departing from a closely spaced parallel runway. During these periods, departures off the upwind parallel runway do not require the normal 2-3 minute wake delay resulting in a safe increase in departure capacity. Wind data is required from the surface up to 1000 ft for this application. WTMD currently utilizes the hourly Rapid Update Cycle (RUC) wind product provided by the National Weather Service. The WTMD wind forecast algorithm is necessarily very conservative due to the fact that the RUC winds are only available on an hourly basis. Even with this limitation, benefits for WTMD are estimated at approximately $200 million *(verify current estimate)*. If information on winds above the airport surface were available from ADS-B, the available periods would likely increase by at least 30%, resulting in an additional benefit of $60 million, based on deployment of WTMD at ten major airports. Some other wake applications are more far-reaching and may result in significantly more benefit.

A.1.2 Additional Capabilities

In addition to supporting future applications that enable wake avoidance and potential reductions in aircraft separation, a number of other important capabilities will also be enabled should airborne derived meteorological data and air-reference data becomes readily available through ADS-B. These include:

- Improved arrival management scheduling and more accurate aircraft trajectory synthesis
- Increased wind field prediction accuracy, and
- Better situational awareness of current weather

A.1.2.1 Improved Arrival Management Scheduling and Aircraft Trajectory Synthesis

A key component in NextGen and SESAR concepts is the use of arrival management scheduling and path synthesis, such as provided by current and next generation NASA CTAS TMA and EDA controller decision support tools. These tools are built on an aircraft trajectory synthesis function that uses path routings, descent profile, and winds aloft to strategically schedule aircraft arrival sequence and required arrival times at critical TMA arrival fixes. Broadcast of ARV and MET data is recommended to support such applications, since this capability provides (1) estimated airspeed for constant IAS/CAS descents from cruise, and (2) wind vector updates for enhanced estimation of ground vector along the selected arrival path to scheduled arrival fixes. Current NASA trajectory synthesis algorithms use nominal descent speeds based on aircraft type rather than planned airspeed descent profiles, which are typically only available on the FMS flight plan, and are not available to current ground automation systems. Similarly, the use of hours-old forecast winds can lead to unreliable sequencing and scheduling of in-bound aircraft. Aircraft derived winds and meteorological data broadcast can be used to update winds-aloft in near real-time, resulting in enhanced reliability of arrival management systems under development for NextGen and SESAR implementation.

There are several different concepts for implementing next generation arrival management systems, each with somewhat different functional requirements. Generally, such systems can be classified as Open Loop arrival management systems if the controller provides explicit descent path and profile instructions which are flown by the pilot or airplane FMS system to the specified arrival fix, or as Closed Loop systems if the airplane avionics provides dynamic inputs such as airspeed guidance to the FMS to achieve desired in-trail sequencing and merging of inbound aircraft prior to reaching the specified arrival fix. Based on simulations and limited flight trials, Open Loop systems typically require more accuracy in the trajectory synthesis function, and controller monitoring of intended path and airspeed compliance, to assure that the aircraft is able to implement the desired arrival trajectory and time schedule. By contrast, Closed Loop systems typically are more tolerant to trajectory synthesis and path following errors, but may require greater pilot situation awareness to assure that in-trail separation with nearby aircraft is achieved.

One means of implementing Closed Loop arrival management is based on ADS-B In surveillance of nearby aircraft. Pilots and potential users of ADS-B In-Trail arrival applications such as VSA and FDMS have consistently recommended the broadcast and display of lead aircraft airspeed for enhanced situation awareness when maintaining desired spacing behind a lead aircraft. In the event that the lead aircraft slows down for merging or as needed for an arrival procedure, the trail aircraft can easily see the difference in airspeed with the lead aircraft, and verify the consistency of speed guidance provided by the ADS-B application. Broadcast of airspeed in this arrival application, allows a pilot to verify, modify, or reject the ADS-B derived speed guidance based on enhanced situation awareness of lead aircraft airspeed.

A.1.2.2 Increased Wind Field Prediction Accuracy

Although use of arriving/departing and nearby aircraft as sensors for measuring wind vector and other MET parameters is an idea that has been around for some time, it is often not economically feasible to use existing data links for this purpose. ADS-B is better structured for regular broadcast of such data. For wind data, it has been shown (Ref. 1) that regular wind updates on the order of minutes rather than hours is essential for reliable arrival management, and for consistency in implementing arrival procedures such as Continuous Descent Arrivals (CDA's). Moreover, earlier studies (Ref. 2) have shown that mixed equipage with 10% or more aircraft broadcasting along path wind data may be sufficient to provide substantial enhancement in local wind field estimation.

A.1.2.3 Better Situational Awareness of Current Weather

Weather paragraph TBD

A.2 Data Requirements

This section describes the data that are needed to support the proposed wake turbulence application. There is general scientific agreement that real-time predictions of the movement and decay of aircraft wake vortices can be developed if ADS-B can provide the following data elements:

- Wind speed
- Wind direction
- Static temperature
- Static barometric pressure[2]
- Aircraft type
- Aircraft position
- Aircraft speed and heading
- Aircraft weight
- Atmospheric turbulence (normally eddy dissipation rate, but total kinetic energy can also be used)
- Aircraft configuration data, e.g., flap setting, for potential future applications

For the mid-term wake avoidance concepts, these data elements are required to be received such that there is a 95% probability of a successful update at the appropriate rate specified in Table A-1. These same data elements provided at the higher air-to-air reception rates shown in Table A-1 will also enable farther-term flight deck-based applications. Aircraft type and position are available from existing ADS-B messages. Aircraft heading and speed can be obtained from existing ADS-B messages, but current rules require it to be sent only in the absence of ground velocity data. These data elements can potentially be obtained from interleaved broadcast of ARV data, or

[2] This data element can potentially be eliminated since it can be computed from pressure altitude broadcast on current ADS-B systems

alternately, reconstructed by the user from ground velocity data and wind vector data as discussed in section A.3.2.

Notes:

1. *Assume moderate to high density traffic environment. For below 5000ft., arrival descent rate of 700-800 fpm. Received rate is for multiple aircraft. Similar resolution to RUC along altitude profile. 10,000ft and below requires higher sampling of profile to capture wind field for downwind, base, and final.*
2. *Received rate is for individual aircraft. Assume climb and descent rates of 2000-3000 fpm. (updates received once every 2000ft?), at least every 5nm laterally. 40 nm range (lower limit) between aircraft to be assisted by ground system needs to be supported (limit due to opposite direction climb/descend thru). Assume 1 in 6 receive rate in TMA airspace.*
3. *Closely spaced parallel approaches, in-trail spacing on final to single runway. Assuming 1 in 4 received at 10nm. Measurement, every 1000 ft nominally.*
4. *Cruise, assume 1 in 8 receive rate in 2035 in highest density airspace at 20nm*
5. *Need weight within 2%. Assume 1 in 10 receive rate in en-route airspace.*
6. *Logic to detect temperature inversions would increase the transmission rate.*
7. *For a maximum of 24 seconds*
8. *Values in this column apply to in-trail geometries only. Update requirements for crossing and head-on geometries need to be considered further and those values added.*
9. *These update rates are not supported by the discussion presented in section A.3.1. Further refinement and more frequent transmission of the meteorological squitter under specific detected conditions may be needed.*

Table A-1 Data Element Received Update Frequency Requirements

Data Element	**Update Period (95% probability) Ground-based Wake System Requirements (surface to 10,000ft profile) See Note 1**	**Update Period (95% probability) Ground-based Wake System Requirements (above 10,000ft) See Note 2**	**Update Period (95% probability) Air-Air Wake system requirements (Far-Term) See Note 3 (up to 10nm range between aircraft)**	**Update Period (95% probability) Air-Air Wake system requirements (Far-Term) See Note 4, 8 (up to 20nm range between aircraft)**	**Update Period (95% probability) Arrival Management Ground-based and Air-to-Air System Requirements (Mid-Term) See Note 5**	**Source**
Wind Speed	60 seconds	40 seconds desired (to be refined, if needed could be obtained from ARV)	15 seconds (to be refined, if needed could be obtained from ARV)	30 seconds (to be refined)	30 seconds (to be derived on user or receive side)	New, see section A.3.1
Wind Direction	60 seconds	40 seconds desired (to be refined, if	15 seconds (to be refined, if needed could be	30 seconds (to be refined)	30 seconds (to be derived on user or receive side)	New, see section A.3.1

		needed could be obtained from ARV)	obtained from ARV)			
Local Temp.	60 seconds	40 seconds desired during atypical atmospheric conditions (to be refined, see Note 9)	60 seconds nominal (15 seconds non-nominal Note 6, Note 7)	120 seconds nominal (30 seconds non-nominal Note 6, Note 7)	N/A	New, see section A.3.1
Local Barometric Pressure	60 seconds	40 seconds desired during atypical atmospheric conditions (to be refined, see Note 9)	60 seconds	120 seconds	N/A	New, see section A.3.1
Aircraft Type	Existing Position squitter	Existing Position squitter	Existing Position squitter	Existing Position squitter	Existing Position squitter	Existing ADS-B Message
Aircraft Position	Existing Position squitter	Existing Position squitter	Existing Position squitter	Existing Position squitter	Existing Position squitter	Existing ADS-B Message
Pressure Altitude	Existing position squitter	Existing position squitter	Existing position squitter	Existing Position squitter	Existing position squitter	Existing ADS-B Message
Aircraft Speed and Heading	Can be derived from aircraft velocity and winds	Can be derived from aircraft velocity and winds	15 seconds received ARV message	30 seconds received ARV message	30 seconds received ARV messages	Winds plus existing ADS-B Velocity and ARV messages, but with revised message transmission rule, see section A.3.2
Aircraft Weight	120 seconds	120 seconds	120 seconds	120 seconds	120 seconds desired	New, see section A.3.1
Atmospheric Turbulence	60 seconds	60 seconds during atypical atmospheric conditions (see Note 9)	60 seconds	60 seconds	N/A	New, see section A.3.1
Aircraft Config.	60 seconds	120 seconds	15 seconds on change (Note 7)	15 seconds on change (Note 7)	N/A	New, see section A.3.1

The update rates in Table A-1 are driven by the need to support various wake vortex and arrival management applications. Flight data is required every 1000 ft or less during departure and arrival phases of flight and every 500 ft or less on takeoff and final approach, where wake turbulence encounters can be the most hazardous.

In addition to the data elements required in Table A-1, it should also be noted that the current wake categories for aircraft in the 1090 ES message set will need to be updated to account for changes that have occurred or will occur over the next few years. A new weight category, Super, has been established to accommodate the Airbus A380 aircraft. Additionally, an effort is currently underway to examine all of the weight categories and determine if new categories should be established based on more than just aircraft weight. Current weight categories are so broad that a single category can encompass aircraft of very different wake generation and wake encounter characteristics. Establishing new categories that discriminate better between groups of aircraft with similar wake characteristics may result in improved operational efficiencies, while maintaining safety.

Section 3 describes two modifications to the current 1090 ES message formats to enable the broadcast of data elements required for the initial wake applications.

A.3 Message Formats and Rates

Two complementary means of deriving wind information from ADS-B messages are proposed. One is through the use of Mode S transponder meteorological data registers: This is described in section A.3.1 and provides the identified data elements in Table A-1. The second is through the existing air-reference vector data format defined in the current DO-260 MOPS, but with a revised transmission schedule. A full description of this method is provided in section A.3.2 and provides the aircraft heading and speed data elements identified in Table A-1.

A.3.1 Design for Aircraft-Derived Meteorological Data Dissemination via Mode S 1090 MHz Extended Squitter (1090ES)

A.3.1.1 Introduction

This section will define a proposed mechanism for the dissemination (both air-to-ground and air-to-air) of aircraft-derived meteorological data by means of the Mode S 1090 MHz Extended Squitter broadcast data link. The proposed mechanism defined in this paper is intended to work in conjunction with the current definition of the Mode S transponder meteorological data registers (44_{16} and 45_{16}) in the transponder. The current definition of the Mode S transponder meteorological registers is intended to support the extraction of aircraft-derived meteorological data by means of addressed interrogations from Mode S surveillance sensors. However, these two Mode S transponder meteorological register definitions are not suitable for applications where ground Mode S surveillance sensors are not available (e.g., over the ocean) and they do not provide for air-to-air cross-link of meteorological data (in particular, cross-link of potentially hazardous, short-lived phenomena such as turbulence or icing). In the future ATC environment supported more and more by "automatic dependent surveillance via broadcast" (ADS-B), the proposed Mode S squitter data link mechanism will provide a compatible means to disseminate aircraft-derived meteorological data along with the ADS-B surveillance information employing Mode S. This proposal defines two new Mode S meteorological registers in a format suitable for the Mode S squitter protocol.

It will be demonstrated that the proposed mechanism for meteorological data squitter fits neatly into the existing design for Mode S. There will be minimal impact on the use of the 1090 MHz spectrum and the proposed design entails minimal extra software processing in the avionics. Expansion space has been reserved for further meteorological data applications as yet undefined.

Note: There is an existing Mode S protocol intended to be employed by ACAS units that allows for addressed cross-link between ACAS-equipped aircraft. This protocol could be employed to directly extract the currently defined aircraft-derived meteorological data registers (4416 and 4516) from another aircraft. However, the use of this protocol requires the system to obtain the Mode S addresses of the aircraft from which data is desired, as well as requiring separate interrogations of each target aircraft to obtain the register contents. Adding this functionality to existing ACAS units is technically possible, but would probably be too costly to support the meteorological data cross-link application envisaged. It appears that the use of the Mode S 1090 MHz Extended Squitter broadcast link would be more efficient and simpler to implement.

A.3.1.2 Proposed Meteorological Squitter Register Formats

The data fields in the proposed meteorological squitter registers defined in this section parallel those already defined in the Mode S transponder meteorological registers 44_{16} (routine data) and 45_{16} (hazard data). The meteorological squitter register formats defined here differ from those used for “ground-initiated Comm-B” (GICB) extraction via an addressed interrogation in that the first 5 bits of the Mode S squitter register contents must contain a “format type code” value which identifies the particular squitter message at the receiver. This proposal for the application of Mode S squitter to the dissemination of aircraft-derived meteorological data assumes that one of the currently reserved Mode S squitter type code values will be assigned to this application. The next two bits of each meteorological squitter register format will be used as a “weather type code” to further identify the particular Mode S squitter message. Two of the four possible meteorological squitter formats will be defined in this section – the remaining two formats are reserved for future expansion of the Mode S meteorological data dissemination application.

Table A-2 defines the first of the proposed Mode S meteorological squitter register formats. Its content closely parallels that of the Mode S routine meteorological data register (44_{16}) already defined for GICB extraction. Other than the incorporation of a 5-bit format type code and a 2-bit weather type code, the differences between Mode S register 44_{16} and meteorological squitter format 1 are:

1. The 4-bit navigational “figure of merit” field from register 4416 is not included here. The Mode S position squitters already provide this sort of information (“navigational uncertainty category” (NUC) in version 0 or “navigational accuracy category” (NAC) in version 1) encoded as part of their format type code values.
2. A wind “quality” flag bit has been incorporated into the squitter definition. This is done because the aircraft roll angle normally extracted via Mode S register 5016 (an element of “enhanced surveillance” (EHS) as part of the Eurocontrol Mode S mandate) is not available via Mode S squitter. The wind quality flag is used to indicate cases of aircraft acceleration where the derived wind measurements would be degraded. The current ICAO Annex 3 specification requires that the wind quality flag be set if the aircraft roll angle exceeds 5 degrees.
3. The resolution of the static air temperature field from Mode S register 4416 is reduced from 1/8 degree C to 1/2 degree C. It is felt that this is a more-reasonable

level of precision to expect from airborne sensors and is sufficient for the expected meteorological applications of this data.

Table A-2 Proposed Meteorological Squitter Format 1

Data Field	# of bits	Range	LSB/Comments
Format Type Code	5	Assigned value	
Weather Type Code	2	Value = 0	
Wind Data Status	1	0=no data, 1=current data	
Wind Quality Flag	1	0=degraded data	|Roll angle| > 5 degrees
Wind Speed	8	0..255 knots	1 knot
Wind Direction	9	0…360 degrees	1 degree
Static Air Temperature Status	1	0=no data, 1=current data	
Static Air Temperature	9	-128..128 degrees C	0.5 degrees C
Average Static Air Pressure Status	1	0=no data, 1=current data	
Static Air Pressure	11	0..2047 hPa	1 hPa
Humidity Data Status	1	0=no data, 1=current data	
Humidity	7	0..100 percent	100/128 percent

Table A-3 defines the second of the proposed Mode S meteorological squitter register formats. Its content closely parallels that of the Mode S hazard meteorological data register (45_{16}) already defined for GICB extraction. Other than the incorporation of a 5-bit format type code and a 2-bit weather type code, the differences between Mode S register 45_{16} and meteorological squitter format 2 are:

1. The windshear and microburst metrics from Mode S register 4516 have been combined into a single data field in squitter format 2. Instead of simply providing a 2-bit metric (none, light, moderate, severe) for each hazard, meteorological squitter format 2 incorporates a signed value for the gain or loss in airspeed involved with the particular hazard. This provides more-useful information about the hazard.
2. Wake vortex generation by an aircraft is impacted by the current configuration of the aircraft. In particular, the configuration of the aircraft's landing gear and its flap setting would be useful in determining the expected intensity of the aircraft's wake. Data on the aircraft's configuration has been added to squitter format 2.
3. The current definition of the squitter "aircraft identification and category" message is able to subdivide aircraft into a set of weight and performance classes as follows:
    a. Light (< 15,000 pounds)
    b. Medium 1 (15,000 to 75,000 pounds)
    c. Medium 2 (75,000 to 300,000 pounds)

d. High Vortex (e.g., B767)
e. Heavy (> 300,000 pounds)
f. High Performance (> 5 g acceleration or > 400 knots airspeed)
g. Rotorcraft

However, more detailed information about the aircraft’s weight would be useful in a number of applications including wake vortex mitigation and determination of an aircraft’s trajectory. ARINC label 075 in the avionics conveys the aircraft’s weight as a 16-bit field employing 40-pound increments. A subset of this weight data has been added to squitter format 2. The proposed weight encoding makes use of the weight classes defined above to provide for a refined weight encoding – the choice of weight LSB is a function of the aircraft weight class (i.e., the encoding LSB used is smaller for lighter aircraft).

It is assumed that the avionics generate a turbulence “eddy dissipation rate” $EDR^{1/3}$ metric sample at least once per minute. A sliding window containing the turbulence metric samples from the most-recent 15 minutes is maintained. The peak $EDR^{1/3}$ value reported is the largest currently contained in the 15-minute window. The average $EDR^{1/3}$ value reported is the average of all the values currently contained in the 15-minute window. The peak delay reported is the number of minutes that the peak $EDR^{1/3}$ value occurs back from the most-recent sample in the 15-minute window.

Table A-3 Proposed Meteorological Squitter Format 2

Data Field	**# of Bits**	**Range**	**LSB/Comments**
Format Type Code	5	Assigned value	
Weather Type Code	2	Value = 1	
Configuration Status	1	0=no data, 1=current data	
Landing Gear Configuration	1	0=down (or fixed gear) 1=retracted	
Flaps Setting	4	0..80 degrees	5 degree steps
Aircraft Weight Status	1	0=no data, 1=current data	
Aircraft Weight	8	See note	See note
Turbulence Status	1	0=no data, 1=current data	
Average Turbulence Metric ($EDR^{1/3}$)	7	0..1.27 in $EDR^{1/3}$ units	0.01 in $EDR^{1/3}$ units
Peak Turbulence Metric ($EDR^{1/3}$)	7	0..1.27 in $EDR^{1/3}$ units	0.01 in $EDR^{1/3}$ units
Peak Turbulence Delay	4	0..15 minutes	1 minute
Icing Status	1	0=no data, 1=current data	

Icing Hazard Metric	2	00=none, 01=light 10=moderate, 11=severe	
Wake Vortex Status	1	0=no data, 1=current data	
Wake Vortex Hazard Metric	2	00=none, 01=light 10=moderate, 11=severe	
Windshear/Microburst Status	1	0=no data, 1=current data	
Windshear or Microburst?	1	0=windshear, 1=microburst	
Airspeed Change Sign Bit	1	0=gain, 1=loss	
Airspeed Change Magnitude	6	0..63 knots	1 knot

Note: If the format type code value encoded in bits 1-5 of the "aircraft identification and category" squitter (BDS register 08 hex) for this aircraft is not 4 (indicating that the aircraft/vehicle category encoding is not using category set A), then the weight encoding uses a default LSB of 2,000 pounds up to a maximum of 510,000 pounds. If the format type code value is 4 for this aircraft, then the weight encoding is a function of the aircraft/vehicle category value (bits 6-8 of the "aircraft identification and category" squitter (BDS register 08 hex)) as defined in Table A-4. If the actual weight to be encoded exceeds the encoding weight maximum from Table A-4, the maximum encode-able weight should be used.

Table A-4 Proposed Weight Encoding for Meteorological Squitter Format 2 (For Aircraft Identification Category A)

Category	Description	Encoding Weight Maximum	Encoding Weight LSB
0	No information	Not Applicable	Not Applicable
1	Light	25,500 pounds	100 pounds
2	Medium 1	76,500 pounds	300 pounds
3	Medium 2	306,000 pounds	1,200 pounds
4	High Vortex	765,000 pounds	3,000 pounds
5	Heavy	1,600,000 pounds	6,400 pounds
6	High Performance	510,000 pounds	2,000 pounds
7	Rotorcraft	510,000 pounds	2,000 pounds

A.3.1.3 Proposed Meteorological Squitter Update Rates

There is always a trade-off between the desire to achieve a certain data update rate and the need to minimize the impact of each application employing the Mode S spectrum. Mode S is primarily intended as an aircraft surveillance system – so, any other use of the Mode S frequencies (such as this proposed meteorological application) must carefully bound its transmission rate. Fortunately, the update requirements for the meteorological data described in this paper are rather modest, and should not have significant impact on the overall Mode S 1090 MHz spectrum utilization.

It is proposed that one meteorological squitter message be generated every 15 seconds. Each active meteorological squitter register (where "active" is defined as having at least one current data item in the register – i.e., at least one status bit is set in the particular meteorological squitter register) will share the meteorological squitter "time slot" in a round-robin fashion. Since there are currently two meteorological registers defined in this proposal, the result will be 3 squitters of each meteorological register each minute. This redundancy ensures a high probability of successful reception of an update of the full meteorological data set once each minute in low to moderate interference environments. *Note: the aircraft identification (a much less dynamic data item) is currently broadcast every 15 seconds.*

Since the data in meteorological squitter register format 2 (see Table A-2) indicates various types of aeronautical hazard conditions, its transmission should take priority over the routine meteorological data contained in meteorological squitter register format 1 (see Table A-1) when a significant hazard is being encountered. It is proposed that if any of the hazard data fields in meteorological squitter register format 2 (e.g., turbulence, icing, wake vortex, windshear, microburst) have current data (i.e., its status bit is set) and are indicating a moderate or severe level of their respective hazard, then meteorological squitter register format 2 will be transmitted in each of the meteorological 10-second slots. This algorithm doubles the update rate for hazardous meteorological conditions (these should be relatively rare events) – while the short-term loss of routine meteorological squitter data during these times should be acceptable. The precise definition of hazard levels is still under development by ICAO METLINK. The current thinking on this area suggests that a peak turbulence $EDR^{1/3}$ value of greater than 0.5 or an airspeed change of greater than 15 knots (windshear or microburst) would be cause to have meteorological squitter register format 2 take precedence over format 1

Since it is highly desirable to reduce the number of squitters generated in order to minimize congestion and interference on the 1090 MHz spectrum, some straightforward rules could be developed to lower the transmission rate of the routine meteorological squitters (format 1) under certain conditions. For example, if the aircraft is cruising (level altitude) above 18,000 feet (where the atmosphere tends to be uniform and stable), then the broadcast rate of format 1 could be reduced to every 30 seconds.

Just because a particular squitter is broadcast does not mean that the squitter will be successfully received by a ground (or airborne) receiver. The probability of a successful squitter reception is a function of:

1. The range between the squitter transmitter and receiver
2. The local interference environment
3. The antenna patterns of the transmitter and receiver
4. The transmitter's power

5. The receiver's sensitivity

Using standard assumptions for (c)-(e) and a low-density interference model for (b) (as derived in Appendix P of RTCA DO-260, the squitter MOPS), the probability of reception for a single squitter is computed to be about 0.68 at 70 nautical miles range, 0.50 at 80 nautical miles, and 0.46 at 90 nautical miles (from Table P-5). Using a worst-case high-density model for 1090 MHz interference (Los Angeles Basin in 2020 with 24K fruit/second as shown in Table P-2) the probability of reception for a single squitter computes to be about 0.68 at 10 nautical miles range, 0.43 at 20 nautical miles, and 0.27 at 30 nautical miles.

The time period in which one can expect to get a successful transmission of squitter data may be computed using the formulas derived in Appendix P of RTCA DO-260 (the squitter MOPS). Assuming a 15-second repetition rate for the meteorological squitter, a 0.5 single-squitter update probability yields a 95 percent probability of a successful update in 60 seconds or less. A 0.4 single-squitter update probability yields a 95 percent probability of a successful update in 90 seconds or less, and a 0.3 single-squitter probability yields a 95 percent update in 120 seconds or less.

These results indicate that one could expect highly reliable transfer of meteorological information within a minute from an aircraft at ranges of about 80 nautical miles in low-density environments and about 10-15 nautical miles in extremely high-density environments. It should be noted that these values are computed for single aircraft. In a dense environment there will be multiple aircraft in a given area of airspace and a successful reception of a meteorological squitter from any one of them is sufficient to characterize the airspace – the multiple aircraft add to the redundancy required to get high squitter reception probabilities.

A.3.1.4 Mode S Transponder Configuration Bits

It could be desirable for ground applications (and cross-link applications) to be able to determine which aircraft have avionics configured to support the new meteorological squitter register formats. It is proposed that a bit in the Mode S "common usage" configuration register (17_{16}) be assigned to indicate whether the given aircraft's avionics are filling at least some data fields in at least one of the proposed meteorological squitter registers.

Note: a bit is already present in register 17_{16} for each of the current meteorological registers 44_{16} and 45_{16}.

A.3.1.5 Summary

This section has proposed a design for the use of the Mode S 1090 MHz Extended Squitter broadcast data link to support air-to-air as well as air-to-ground dissemination of aircraft-derived meteorological data. The proposed design is a modest extension of the Mode S transponder register set (44_{16} and 45_{16}) already defined to support extraction of aircraft-derived meteorological data via addressed interrogations by a ground Mode S surveillance sensor.

Note: as mentioned at the beginning of this section, these currently defined transponder meteorological registers could also be extracted via the ACAS cross-link protocol.

The use of the Mode S squitter broadcast data link provides a means to disseminate aircraft-derived meteorological data in areas lacking Mode S ground support or where

ATC will be done using ADS-B. Simple and inexpensive Mode S 1090 MHz Extended Squitter receivers could be used to obtain the meteorological data. Aircraft could obtain desirable meteorological “situational awareness” (local winds, turbulence hazards, regions of current icing, etc.) directly from the other aircraft around them.

It has been shown that the proposed design for meteorological squitters entails a low impact on the Mode S 1090 MHz spectrum. The requirements for avionics support would also be low. Given that an aircraft is equipped with the appropriate sensors to derive meteorological data (e.g., it would only require a GPS navigation system to be able to make wind measurements – and such equipment would likely already be onboard an aircraft equipped to support Mode S Extended Squitter), then only reformatting software in the avionics would be required to fill the necessary Mode S transponder registers and a modest change to the transponder software to squitter the new meteorological registers at the required rate.

It must be noted that this proposal should be reviewed for both its meteorological and Mode S application aspects. Is the data in the proposed definitions from section 2 above sufficient and complete? Is the data update rate proposed in section 3 above adequate? Is the impact of these additional Mode S squitters acceptable on the Mode S 1090 MHz spectrum? If all these questions can be successfully answered, then the Mode S meteorological application proposed here would make a useful addition to the aeronautical world.

A.3.2 Broadcast of Air-Reference Vector for Future Airborne and Air-Ground Applications

In the current DO-260 and DO-260A extended squitter MOPS, air-reference velocity information such as airspeed and magnetic heading data are input to extended squitter systems, but are not broadcast in ADS-B messages except in the very rare event that no ground velocity data such as GPS velocity vector is available from airborne avionics. This section proposes the broadcast of air-reference vector (ARV) data interleaved with ground vector data at a low rate, i.e., one out of ‘N’ velocity broadcasts would contain ARV data rather than standard ground vector outputs when ground vector and ARV data outputs are both available. This proposal would use the existing ARV inputs and data formats defined in earlier DO-260 MOPS, but would transmit ARV data periodically and enable wind vector derivation by ADS-B user applications.

In this section we show the feasibility of deriving wind vector (on the receive side) given joint broadcast of ground vector and ARV data. This capability will be particularly valuable for aircraft that do not have the capability to output wind and MET data. Finally, this section outlines the concept of ARV “coasting” whereby current ARV outputs can be estimated using current ground vector and wind vector data, which leads to a more efficient protocol for ARV broadcasting, minimizing the needed rate of ARV broadcasts for reliable reception in 1090 Mhz frequency congested airspace.

It should be noted that interleaved ARV broadcasts would not increase aircraft squitter rate, i.e., data content in state vector messages is enhanced with no increase in spectrum congestion or need for increased squitter rate.

A.3.2.1 Wind Triangle and Derivation of Wind Vector from Ground Vector and ARV Data

In order to fly an aircraft on a desired track or course over the earth, it is necessary to point an aircraft slightly into the wind so that the aircraft follows the desired track, i.e., the pilot or autopilot adjusts the heading of the aircraft to achieve a desired mean track for the current flight segment. The assumed relationship between the air-reference velocity vector (True airspeed or TAS, and True heading angle), the mean wind vector, and the ground velocity vector is a two-dimension vector shown in Figure A-1, and known simply as the wind triangle. (The analysis in this Appendix assumes a simplified, flat-earth coordinate system.) In this figure, the aircraft is positioned at the origin and the wind triangle gives the ground referenced velocity of the aircraft, given aircraft air-mass velocity and the current wind vector. The wind triangle assumes that the ground vector is the horizontal vector sum of the air-reference vector and the mean wind, i.e., that the mean wind at a given altitude is primarily a horizontal velocity that adds to the aircraft propulsive velocity vector to achieve a specified course over the earth. (In this terminology, ARV is defined to be TAS and True heading, whereas the more typical broadcast quantities of IAS/CAS and magnetic heading need to be converted to True airspeed and True heading prior to any analysis using the wind triangle relationship.)

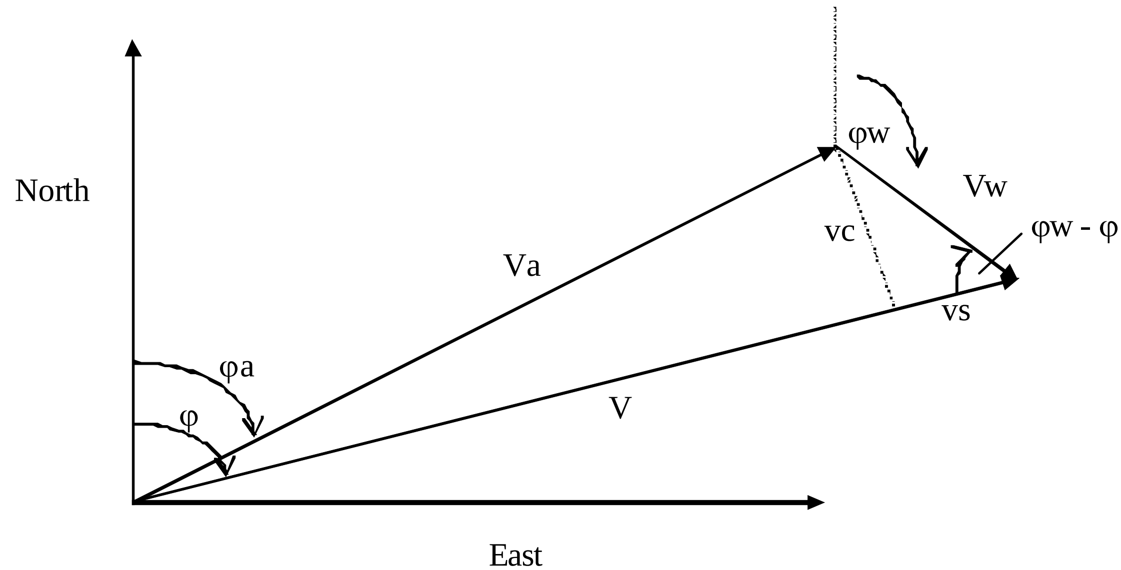

Figure A-2 Wind Triangle for Modeling Aircraft Velocity Relationships

In the above, (φ , V) denotes earth reference track angle and ground speed, (φa , Va) denotes air-mass true heading and airspeed, and (φw , Vw) denotes current wind direction and wind speed. The along-track and cross-track wind components are denoted vs and vc in Figure A-2. The air and earth referenced quantities satisfy the following relationships which are easily derived from Figure A-2:

$$\sin(\varphi - \varphi a) = vc / Va \qquad (2.1)$$

$$Va^2 = vc^2 + (V - vs)^2 \qquad (2.2)$$

The above equations may be used to coast true airspeed and true heading, given ground vector from ADS-B broadcasts, and derived wind vector. (See section 3.0)

The important point to be emphasized with the wind triangle is that given any two legs of the triangle, the third leg can be estimated. In the next section we show how the wind vector can be estimated given current estimates of the ground vector and air-reference vector obtained from ADS-B broadcasts. It is also possible to use ground vector and the wind vector to estimate the air-reference vector, or alternately, to use air-reference vector and the wind vector to estimate the ground vector. This is the basis of ARV coasting and ground velocity coasting, respectively, when current estimates of those quantities are not available from recent ADS-B broadcasts.

It should be noted that the wind triangle relationships are based on the following modeling assumptions:

- **The wind vector is primarily horizontal, with generally small contributions in the vertical axis. -** This assumption is generally valid, but may not hold in certain circumstances, e.g., due to downdrafts when nearby and below high mountain ranges, and due to local weather disturbances which can give rise to phenomena such as clear-air turbulence and vertical micro-bursts. Generally, the wind triangle is valid as a horizontal axis projection of the full 3-D wind triangle, provided that the aircraft flight path angle is small. This assumption is valid for most civil aircraft, at least during descent and climb-out after the aircraft has a clean configuration with flaps and landing gear retracted.
- **The effect of wind gusts and local wind disturbances on aircraft motion is primarily to increase process noise on the aircraft trajectory. -** This assumption means that the aircraft guidance system is able to maintain the desired flight course and speed with only minor variations in trajectory path due to wind gusts and higher frequency wind dynamics.
- **The lag between reception of current ground vector and ARV data is small**, i.e., the difference between the ground vector and the air-reference vector primarily reflects the wind vector with minimal error due to aircraft acceleration dynamics.

Note: Assuming that the wind vector is small in the vertical plane, resolving the forces in the vertical plane and assuming small flight path angles yields

$$dh/dt = Va*\gamma a = V*\gamma$$

where h is the geometric altitude relative to earth fixed axes, γa is the flight path angle relative to the wind (assuming small flight path angle), and γ is the flight path angle of the aircraft relative to fixed inertial axes. These equations enable the flight path angle relative to the wind and in inertial axes to be calculated given GPS measurements of geometric vertical rate. The rate of change in vertical pressure is related to geometric vertical rate by the relationship (Ref. 3)

$$dhp/dt = (Tsd(hp) / Tk(hp)) * dh/dt$$

where Tsd (hp) is the static temperature for the standard atmosphere at pressure altitude hp, and Tk denotes the actual or measured temperature at pressure altitude hp derived from radiosonde measurements or MET broadcasts from one or more aircraft in flight. The last equation can be used by an ADS-B user to convert from geometric to pressure altitude rate, or vice versa. If the user is another ADS-B aircraft, then Tk can also be estimated based on ownship measurements of Delta_ISA, i.e.,

$$Tk(hp) \sim Tstd(hp) + Delta\_ISA,$$

where $Delta\_ISA \sim Tk(ownship) - Tsd(hp(ownship)).$

A.3.2.2 Derivation of Wind Vector from Ground Vector and Low Rate ARV Broadcasts

Given a received broadcast of position state and ARV data, typically in the form of IAS/CAS airspeed and magnetic heading, and the most recently received ground vector, it is feasible to use the wind triangle relationship above to derive current estimates of wind vector. The derivation process is described using the flow diagram shown in Figure A-3. In this diagram, the input parameters from ADS-B broadcasts are shown in the upper left corner, using bold input arrows, and the main functional blocks leading to estimates of wind speed and wind direction are illustrated. (The detailed calculation procedure is not specified here, since this Appendix focuses on the ADS-B out parameters, rather than on receive side functions. For details, see Ref 4, 5.) The first functional block in the process converts CAS to Mach number and Magnetic Heading to True Heading, assuming a standard atmosphere. **It is recommended that Mach number be input to the transponder rather than CAS airspeed, in the event that the aircraft is flying a constant Mach number**. (This simplifies the calculation process and is consistent with aircraft guidance laws that switch from CAS to Mach guidance above a fixed transition altitude.) Pressure altitude is needed in the conversion from CAS to MACH to estimate pressure ratio (delta). In addition, pressure altitude is used to estimate temperature ratio (theta) for MACH to TAS conversion. (Somewhat better accuracy can be obtained in this process if the measured theta or delta temperature (Delta ISA) between the measured atmosphere and a standard atmosphere is known on the receive side, and used to compensate for a hotter or colder than standard day.) Similarly, the magnetic deviation between magnetic and true North can be estimated using the aircraft horizontal position to convert from magnetic to true heading. Once true heading and TAS are obtained, the wind vector can be computed by subtracting the air-reference vector from the ground vector in North and East components, and then converting the result to desired wind speed and direction outputs.

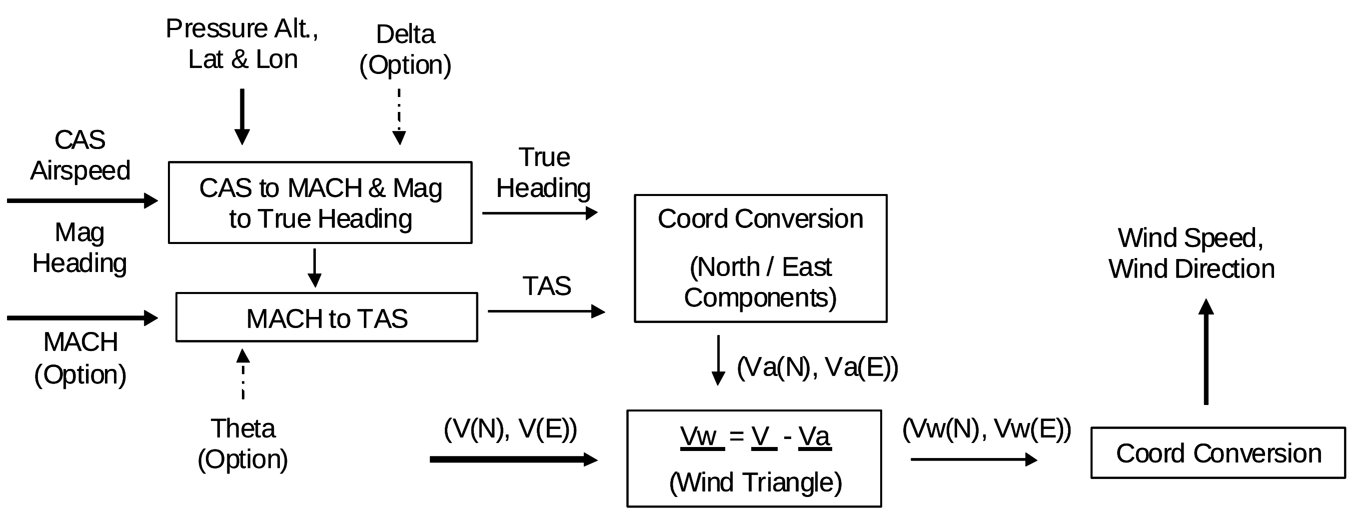

Figure A-3 Derivation of Wind Vector from Received ARV and State Vector Data

A.3.2.3 Proposed Update Rates for Wind Vector and ARV Broadcasts

With the wind vector derivation described above, nominal broadcast of ARV data may be compatible with that needed for air-ground MET broadcasts. The recommended broadcast of MET data in RTCA document DO-252, for example, varies from 3 minutes nominal update rate at cruise altitude to between 20 and 60 seconds for climbs and descents from the TMA to cruise altitude. In descents to TMA airspace, 40 second updates at 95% probability are considered adequate for general MET applications. However, at lower altitudes, within about 2,000 meters AGL, weather conditions can change more rapidly with altitude as an aircraft transitions the planetary boundary layer of the atmosphere. Consequently, **a compromise value of 30 seconds is proposed for 95% update interval of received ARV data for computing wind vector** for arrival management, (5th column of Table A-1).. It is recommended that the proposed update rate and Conops for deriving wind vector be verified for critical approach procedures, by future ARV broadcast data trials and simulation analysis, prior to standardization in a future DO-260 MOPS implementation.

For critical air-to-air wake vortex applications, the received update rate for ARV broadcasts is determined by the 3rd and 4th columns of Table A-1, i.e., 15 seconds 95% update interval for lead-trail aircraft distances less than 10 nm, and 30 seconds 95% update interval for nearby aircraft less than 20 nm. In the first case, a 4 to 1 ratio is assumed for transmit rate to receive rate resulting in a minimum transmit interval of 15 / 4 = 3.75 seconds, i.e., at least one ARV message broadcast each 3.5 second time interval, assuming interleaving of ARV and ground vector broadcasts. The 30 second requirement for distances less than 20 nm yields the same 3.75 second minimum transmit interval for ADS-B In wake vortex applications, since the transmit rate to receive rate is assumed to be 8 to 1 for air-to-air ranges less than 30 nm.

A similar analysis for the arrival management applications and for ADS-B In reception of ARV data within 30 seconds in congested airspace yields similar results. Suppose that ARV data is broadcast 1 out of N velocity squitters, i.e., ground vector is broadcast for N-1 consecutive velocity squitters followed by an ARV velocity squitter. In a high-density interference environment, a single squitter needs a probability of reception p1>= 0.25 to assure reliable reception of position data out to 30 nm, i.e., 95% probability of reception within 5 seconds, assuming 2 squitter / sec broadcast rate. It is assumed that a single squitter reception probability p1= 0.25 or better is also required for broadcast of ARV data. Then to achieve an assured 95% probability of reception within 30 seconds yields the following single squitter probability levels:

N=4: p1>= 0.17

N=6: p1>= 0.25

N=8: p1>=0.33.

From this analysis we conclude that for 95% reception probability of at least one ARV broadcast within 30 seconds in a high-density interference environment, N=6 is the largest allowable interleaving ratio for velocity squitters, i.e., **ARV data needs to be broadcast at least once every 3 seconds to assure reliable ADS-B In reception of ARV data within 30 seconds in a high interference environment.**

On the basis of this analysis, N=6 is recommended for interleaving ARV broadcasts and ground vector broadcasts as a means for estimating wind vector.

Note: If an 8 to 1 ratio can be assumed due to ground infrastructure enhancements in dense Terminal and En-Route airspace, then the requirement for ARV broadcast updates can be relaxed slightly to 30 / 8 = 3.75 seconds or N=7 for interleaving ARV and ground vector broadcasts.

A.3.2.4 Data Coasting for Continuity of ARV Data During Gaps in ARV Reception

One problem with broadcasting ARV data at a low rate, is that there may be long gaps in ARV reception, whereas applications such as In-Trail following procedures may need to refresh ARV data for airspeed display at a faster nominal rate, say on the order of 5 seconds, for consistency with refresh and display of other state vector data. Although the wind vector may need updating at longer intervals, air-reference vector should be updated more frequently due to the presence of aircraft turn maneuvers and other acceleration dynamics. Fortunately, there is a lot of redundancy between the ground vector and the air-reference vector that potentially allows the use of ground vector and the wind triangle as a means of filling in the gaps in ARV reception, i.e., using the high refresh rate ground vector and the slowly changing wind vector to solve for air-reference vector, and reversing the flow in Figure A-3 to solve for IAS/CAS airspeed and magnetic or true heading as needed.

It is not necessary to use measured ground vector directly in this process, i.e., continuity of state data is typically best served using a state vector tracker that updates the aircraft position and ground velocity whenever new position or velocity messages are received. Suppose that (φ*, V*) denotes the current track and ground speed estimates for ADS-B In or ground based surveillance, and (φw , Vw) denotes the current wind direction and wind speed, respectively. Then, from equation 2.2, TAS is given by

$$TAS = (vc^2 + (V^* - vs)^2)^{1/2}$$

where from Figure A-1, the cross-track and along-track wind components are given by

$$vc = Vw^* \sin(\varphi w - \varphi^*)$$

$$vs = Vw^* \cos(\varphi w - \varphi^*)\ .$$

(If needed, true heading can also be computed from equation 2.1 by back-solving for φa.)

Given TAS, the pressure ratio (delta) and the temperature ratio (theta), CAS can be computed directly, i.e.,

$$CAS = f(delta, theta, TAS),$$

where the function f is given explicitly in Ref. 5. The temperature ratio can be computed directly using pressure altitude and standard atmosphere assumptions, or more accurately using measured data such as recent radiosonde plots or MET broadcasts of temperature. The pressure ratio can be computed directly as a function of pressure altitude, depending on whether pressure altitude is above or below the tropopause (~36,000 ft). The resulting CAS value is proposed as a means of coasting airspeed during gaps in received ARV data.

Note: The same concept applies for coasting ground velocity in the event that GPS velocity is lost for some time period. In this case, ARV data is broadcast at a high rate and ground vector can be estimated using the wind triangle and calculations similar to that shown in Figure A-3, except that air-reference and wind vector are added together to estimate ground vector.

A.4 Provisioning (TBD)

Practical discussion of how the needed information could be made available to the transponder on an aircraft

ARINC labels (identify which are currently available and which bus they are on, and which need to be made available)

A.5 References

[1] R.E. Cole, S.Green, et al., "Wind Prediction Accuracy for Air Traffic Management Decision Support Tools," 3rd USA/Europe Air Traffic Management R&D Seminar, Napoli, Italy, June 2000.

[2] D.A. Forrester and G.C. Dean, "Improvement of Meteorological Data for Air Traffic Management Purposes," Air Traffic Control Quarterly, Vol. 2, No. 2, pp 85-101, 1994.

[3] J.W. Burrows and A. Chakravarty, "Time-Controlled Aircraft Guidance in Uncertain Winds and Temperatures," 1984 American Control Conference, San Diego, Ca., 1984.

[4] R. Slattery and Y. Zhao, "Trajectory Synthesis for Air Traffic Automation," Journal of Guidance, Control, and Dynamics, Vol. 20, No.2, March 1997.

[5] CAS to TAS conversion equations reference