Optimization Requirements Document for the Meteorological Data Collection and Reporting System/ Aircraft Meteorological Data Relay System

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Optimization Requirements Document

1.0 Summary

This document presents the requirements and justification for an Optimization System for the Meteorological Data Collection and Reporting System (MDCRS) that will enable selection of specific aircraft to provide essential weather observations to meet the government's needs while reducing redundant and unnecessary data. MDCRS is a private/public partnership within the U.S. that facilitates the collection of atmospheric measurements from commercial aircraft to improve aviation safety. (MDCRS is similar to the Aircraft Meteorological Data Relay (AMDAR) system that has been implemented in other parts of the world; therefore, the term MDCRS/AMDAR is used in this document to refer to the general program within the U.S. for collecting weather observations from aircraft.) The MDCRS/AMDAR system receives Aircraft Communications Addressing and Reporting System (ACARS) messages containing meteorological data from participating aircraft, processes the messages and forwards the encoded data to NOAA's National Centers for Environmental Prediction (NCEP), where they are used in weather forecasting models. The system has been in place since 1995 and can arguably be said to provide better and more timely information to weather forecasters than is possible by any other means. High quality meteorological data enable more accurate forecasting of hazardous weather, which directly contributes to the FAA's goals to increase safety and capacity in the NAS and benefits the airlines directly. Seven airlines with a total of about 1,600 aircraft operating out of approximately 50 airports in the CONUS participate in the MDCRS/AMDAR program. Meteorological observations are collected during the ascent, en-route, and descent phases of flight. The cost of communications is approximately $60K per month. Because of the nature of airline operations, an excessive number of reports come from a few areas of the country while there are large areas of the country from which very few reports are obtained.

The Government envisions a system that fills critical gaps in the current coverage and is cost-effective. Coverage can be improved by adding regional aircraft that operate from smaller airports, but increasing the number of participating aircraft will increase the communications cost and consume more of the data link system capacity.

An Optimization System would enable the selection of specific aircraft to provide only the essential data to meet the needs of the forecasting agencies and allow data to be collected from regions that are not well covered without increasing the communications costs or the required data link bandwidth.

1.1 Purpose

The purpose of this document is to present the requirements and justification for an Optimization System for the MDCRS/AMDAR program that will enable selection of specific aircraft to provide essential data to meet the government's needs, while reducing redundant data. Section 2 describes the MDCRS/AMDAR system and explains its importance. Section 3 describes the desired state of the system as stated by the NOAA customers. Section 4 presents the concept for an optimization system and Section 5 describes a transition to full implementation of the Optimization System. The next steps in the process are presented in Section 6.

2.0 Overview of MDCRS/AMDAR

MDCRS is a private/public partnership within the U.S. that facilitates the collection of atmospheric measurements from commercial aircraft to improve aviation safety. The MDCRS/AMDAR system receives ACARS messages containing meteorological data from participating aircraft, decodes the messages, encodes the data into Binary Universal Format Representation (BUFR), and forwards the encoded data to NOAA's National Centers for Environmental Prediction (NCEP) where they are used in weather forecasting models.

The architecture of the MDCRS/AMDAR system is shown in Figure 1 below.

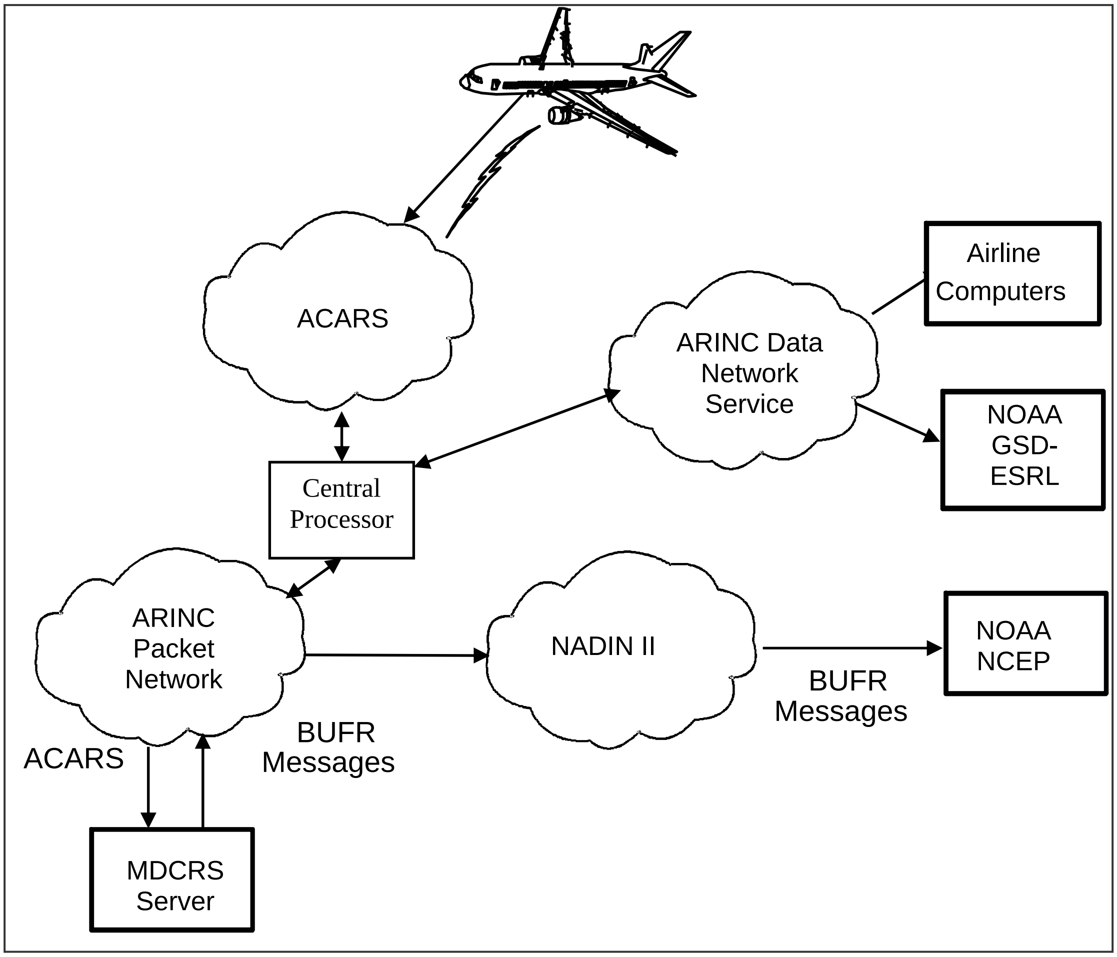

Figure 1. MDCRS System Architecture

MDCRS/AMDAR messages are a small fraction of the total number of data link messages received from aircraft. The winds and temperature measurements that are the core of the MDCRS dataset are obtained from the aircraft's navigation system and flight management system. Most modern jet transport aircraft, including regional jets, are equipped with data link systems and are capable of providing MDCRS/AMDAR data with no modification to aircraft systems other than the installation of software provided either by the avionics manufacturer or the aircraft operator. Currently, only a small portion of the total MDCRS/AMDAR fleet provides water vapor or turbulence measurements, however, systems are now available to add that capability to most commercial transport aircraft.

2.1 Importance of the MDCRS/AMDAR System

The MDCRS/AMDAR system has been routinely collecting aircraft observations since 1995 and can arguably be said to provide better and more timely information to weather forecasters than is possible by any other means. In February 2003 the American Meteorological Society issued a statement in support of automated observations from U.S. commercial aircraft, which reads in part:

"The United States Meteorological Data Collection and Reporting System (MDCRS) has become an extremely useful asynoptic data source allowing for the measurement and dissemination of real-time wind, temperature, humidity, and turbulence data from commercial aircraft and enabling a significantly better understanding of atmospheric conditions. There is a wealth of documented evidence that this dataset, along with its international equivalent, Aircraft Meteorological Data Relay (AMDAR), has led to improved weather forecasts that benefit the public at large and contribute to improved safety and efficiency of flight operations.

*"The MDCRS is a rich source of meteorological data providing critical input to numerical forecasts and to meteorological analyses. Studies have shown that MDCRS and AMDAR observations improve both the initial analyses and model forecasts of the upper air, which contribute to safer and more efficient aircraft operations. The future success of the MDRS and AMDAR programs depends on a partnership between the airline operators and the federal government, and shared responsibility for continued viability. This important national resource must be nurtured so as to improve the safety and comfort of passengers, and provide economic benefit to operators through fuel savings and more efficient flight routing when bad weather is anticipated." (Bull. Amer. Met. Soc., **84**, 515-517)*

High quality meteorological data enable more accurate forecasting of hazardous weather, which directly contributes to the FAA's goals to increase safety and capacity in the NAS. Three of the Transformation Directions stated in the Joint Planning and Development Office's (JPDO) Next Generation Air Transportation System Integrated Plan (NGATS) directly relate to forecasting accuracy and the MDCRS/AMDAR system. They are:

- Improve accuracy and timeliness of aviation weather information, allowing NGATS to proactively, versus reactively, respond to weather.
- Enhance aviation safety and capacity through the use of weather support tools that increase the operational focus, relevance, and accuracy of weather predictions, and leverage technology to improve scientific understanding, efficiency, capability, and communications.
- Promote advances in weather technologies from major breakthroughs in our scientific understanding of weather, major improvements in weather sensor technology, and a vast increase in the number and type of weather measurements made from ground-, satellite-, and aircraft-based sensors.

MDCRS/AMDAR is one of the important data sources used by NOAA meteorologists to produce aviation weather forecasts. Meteorologists frequently cite MDCRS/AMDAR (or ACARS) as a source of data in area forecast discussions. For example, MDCRS/AMDAR data show temperature inversions with sufficient accuracy to forecast ceiling heights and visibilities at the airports in the Los Angeles basin. These data are also useful in forecasting wind gusts and low level wind shear in the terminal areas. MDCRS/AMDAR data are used in the NCEP RUC model, which was developed to serve the U.S. aviation interests, and are the only hourly *in-situ* atmospheric observations that are assimilated into that model. MDCRS/AMDAR data are also one of the important data inputs to the FAA's Integrated Terminal Weather System (ITWS) that is being deployed at 46 major airports.

The airlines directly benefit from the improved aviation weather forecasts. Examples are:

- Accurate wind forecasts in the high troposphere enable efficient routing and fuel savings.
- Greater predictability of the timing, location, and intensity of weather hazards allows better selection of air routes that support traffic volumes and minimize delays or diversions.
- The subjective application of MDCRS/AMDAR data by individual forecasters improves the forecasting of local conditions such as freezing levels and aircraft icing, the phases of precipitation reaching the ground (rain, freezing rain, sleet, or snow), wind shear profiles and turbulence, or the potential for fog or convection. Each of these factors directly relate to safety and efficiency of operations.
- Accurate and detailed forecasts of temperature, wind, clouds, and storms have a direct bearing on aviation safety.

2.2 State of MDCRS/AMDAR

Seven airlines with a total of about 1,600 aircraft currently participate in MDCRS/AMDAR system and provide about 2,500 soundings per day to the NWS. The participating airlines are: American, Delta, Federal Express, Northwest, Southwest, United, and United Parcel Service. Each observation includes wind and temperature measurements, at a minimum, and may include measurements of water vapor, turbulence, and icing. A breakdown of the number of participating aircraft by airline and airframe is shown in Table 1.

American	270
Delta	476
Fed Ex	159
Northwest	72
United Parcel Service	120
United	431
Southwest	55

Table 1a. Number of participating aircraft for each airline

737	333
757	490
767	221
777/747	79
MD10/11	90
MD88/90	136
A300	234

Table 1b. Number of participating aircraft of each airframe

Data from the meteorological observations are collected during the ascent, en-route, and descent phases of flight. The ascent phase is the period from takeoff to top-of-climb (TOC), when the aircraft's altitude stops increasing and becomes nearly constant. The descent phase is the period between top-of-descent (TOD), when the aircraft's altitude starts to decrease, to touch-down or landing. En-route is the segment between TOC and TOD, when the aircraft's altitude is relatively constant. The observations most useful to NOAA are those made during the ascent and descent phases of flight. These are referred to as "soundings", where a sounding typically includes about 40 observations.

Most of the operations of the seven participating airlines are from approximately 50 airports in the CONUS. Because of the hub and spoke nature of airline operations, an excessive number of reports come from a few areas of the country and few reports come from other areas. NOAA has stated a need for a minimum of one sounding every two hours; a requirement that can be met with one or two ascent soundings per hour from each terminal, or about 18 to 48 soundings per day, assuming that terminal operations occur within a period from 6:00am to midnight each day. Airports (or terminal areas) that provide an average of more than 60 soundings per day are listed in Table 2 below, based on data provided by NOAA for a one week period in April 2005.

Terminal Area	**Soundings per day**
Memphis, TN (MEM)	208
So. CA (LAX, SAN, ONT, BUR)	170
Chicago, IL (ORD)	157
Minneapolis, MN (MSP)	151
No. CA (SFO, OAK, SMF. SJC)	136
New York Metro (JFK, LGA, EWR)	135
Detroit, MI (DTW)	131
So. FLA (MIA, FLL, PBI)	125
Denver, CO (DEN)	100
Atlanta, GA (ATL)	88
DC Metro (IAD, DCA, BWI)	64
Louisville, KY (SDF)	64
Central TX (DAL, DFW, AFW)	64

Table 2. Terminal areas that provide more than 60 soundings per day.

There are large areas of the country from which very few soundings are obtained. Figure 2, Average Daily MDCRS Aircraft Soundings (Ascents and Descents), which was provided by NOAA, shows the average daily number of soundings per day (2,227) from 79 airports for a representative period. (The four regional airport areas shown in blue, NYC, DFW, SFO, and LAX, are each counted as one terminal area.)

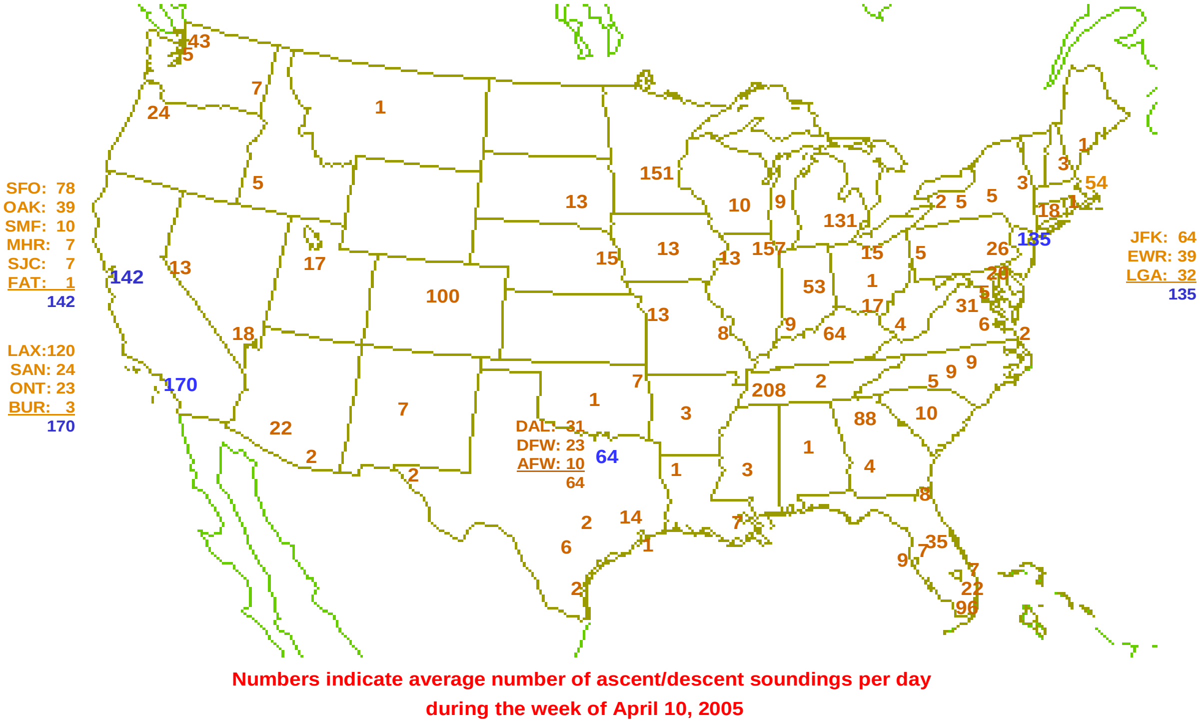

Figure 2. Average Daily MDCRS Aircraft Soundings
(Ascents and Descents)

The top 51 airports provided a total of 2,150 soundings and each provided 6 or more soundings. (Note: These data were collected before Southwest Airlines started participating in the program.)

2.3 Communications Services

Communications are provided by ARINC, the data link service provider for the participating airlines, and include the air-to-ground data link and ground-to-ground links from ARINC's communications processors to the airlines' host terminals and to NOAA's centers in Silver Spring, MD and Boulder, CO. The cost of communications is approximately $60K per month, with half paid by the airline participants and half by the Government.

2.4 Stakeholders

Stakeholders in the MDCRS/AMDAR system include:

- Government users
  - NOAA – receives processed observations and uses the data in forecasting models and for research purposes.
  - FAA – uses the data in operational systems such as ITWS to develop advisory information for the aviation community. Partners with NOAA to provide weather forecast information to users of the NAS.
- Airline participants – benefit directly from improved weather products and from direct viewing of processed observations.
- Others – many elements of society benefit from improved weather warning, watch and forecast services enabled by MDCRS/AMDAR.

3.0 Desired End State of MDCRS/AMDAR

The Government envisions a MDCRS/AMDAR system with the following characteristics:

- Fills the critical gaps in the current horizontal coverage.
- Provides uniform vertical coverage, especially at the most important altitudes from ground to FL250.
- Provides measurements that are uniformly distributed in time.
- Allows targeting areas of special interest such as the build-up of significant weather-driven events.
- Is cost-effective.

3.1 Filling Coverage Gaps

Achieving the Government's desired end state of increased coverage in areas where coverage is now poor or non-existent requires the participation of more aircraft and more airlines, especially regional airlines. NOAA has suggested that adding aircraft that operate out of 50 airports not currently covered would fill the most significant gaps in horizontal coverage. Figure 3, which was provided by NOAA, shows the geographic distribution of the current 50 MDCRS/AMDAR airports plus an additional 50 airports that are designated as "Future MDCRS/AMDAR Airports".

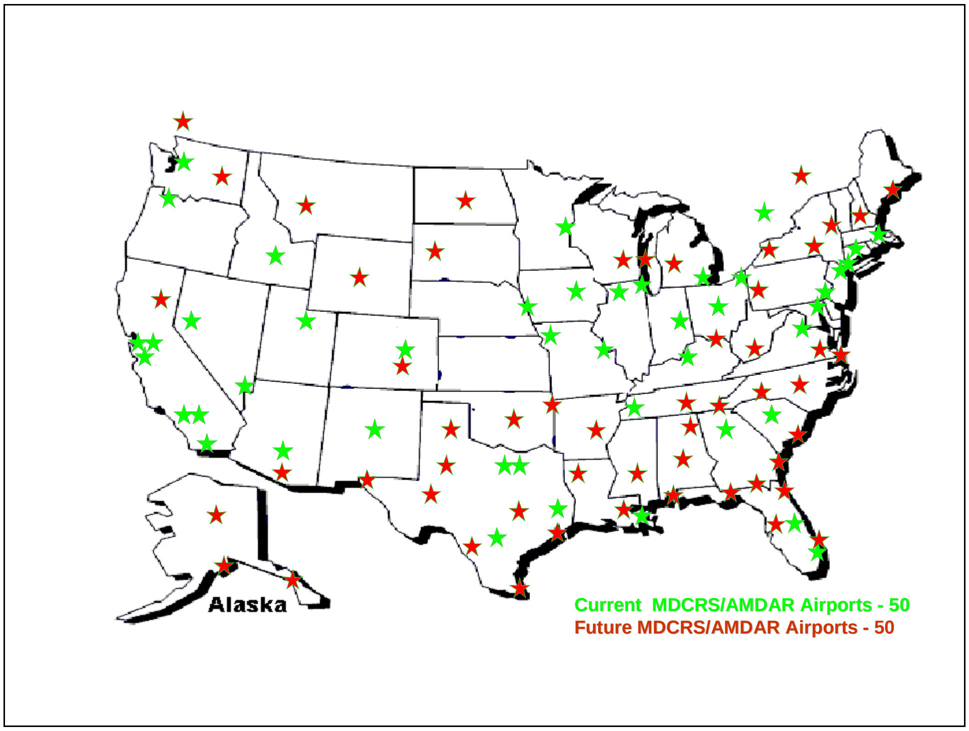

Figure 3. Distribution of Current and Future MDCRS/AMDAR Airports

There are consequences associated with increasing the number of participating aircraft that must be considered. One is that as the number of MDCRS/AMDAR data link messages increases, the total communications cost will increase. A second consequence is that the total volume of data link messages will increase not only at the "new" airports, but also at the existing airports, which serve as one end point of many of the routes that would be added. At many of the larger airports, ACARS traffic has already reached the point congestion and additional MDCRS/AMDAR messages will exacerbate that condition.

3.2 Achieving Cost Effectiveness

The number of messages transmitted and the cost of communications will increase as the number of participating aircraft increases unless some means is used to limit the number of messages. Transmitting only those messages that are unique and eliminating excessive and redundant messages, especially in high traffic areas, could be an effective means towards achieving greater cost effectiveness.

The airlines have clearly expressed their desire to reduce the cost burden on them of providing the MDCRS/AMDAR data and could be expected to reduce the number of MDCRS/AMDAR messages transmitted unless relief is provided in some other manner. This would lead to the Government paying all communications costs rather than approximately half the costs, as is the current situation.

It is reasonable to expect that, as aircraft are added to improve coverage, communications costs could double or triple. Therefore, it becomes very important to reduce the number of messages transmitted to the ground to eliminate excess data, particularly around major hub airports.

3.3 Aircraft Requirements

Modern jet transport aircraft have avionics systems that conform to industry standards. The ARINC Specification 620 is a data link system standard and interface specification developed by the Airlines Electronic Engineering Committee (AEEC) to set forth the desired interface characteristics for the data link user. It provides, among other things, a standard message format for downlink meteorological reports (from the aircraft to the ground) and for uplink commands that can be used to configure aircraft systems for reporting meteorological data. This standard has evolved over the years and many participating aircraft do not conform precisely to the current standard, but the trend is toward greater conformance both on the part of aircraft operators and avionics manufacturers. As aircraft conform to the ARINC 620 standard, an optimization system as described below can be effectively used to manage the collection of MDCRS/AMDAR data by sending uplink messages in a standard format that can turn on or off the meteorological reports.

A summary of the ARINC 620 meteorological report format is provided in the Appendix of this report. Figure 4 provides a graphic representation of typical MDCRS/AMDAR reporting during the various phases of flight.

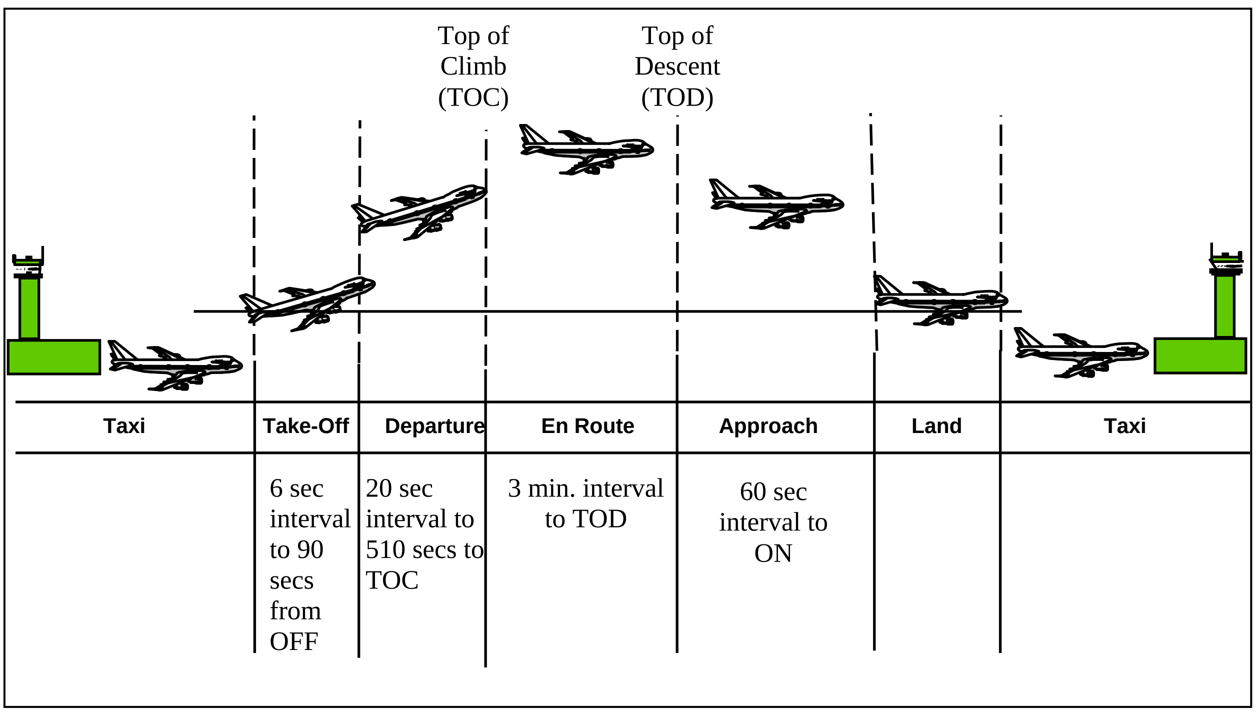

Figure 4. Typical MDCRS/AMDAR observations

4.0 Objective of an Optimization System

An Optimization System would enable the selection of specific aircraft to provide only the essential data to meet the needs of the forecasting agencies, while eliminating non-essential data as a means of limiting and controlling communications costs.

All participating aircraft are capable of reporting winds and temperature data and some aircraft equipped with water vapor sensors also report moisture data. In the future some aircraft will be able to report turbulence and icing events as they occur.

In the current operation of MDCRS/AMDAR, aircraft continuously collect and send observations to the ground depending on how the avionics system is configured by the operator. In most cases, an aircraft will begin collecting data from the moment it lifts off the runway and will not stop until it lands at its destination. Some operators have configured aircraft to send reports less frequently or only during the ascent phase of flight in order to reduce the number of messages and the communication cost.

The Government has determined that data collected during the ascent phase of flight are the most useful, with descent reports being the next most useful. Data collected during the en-route phase of flight are useful but of less value.

4.1 Optimization System Requirements

Aircraft equipped with avionics systems that respond to uplink messages in ARINC 620 format can participate in an optimization program. An optimization system can be implemented that would send commands to these aircraft to configure their meteorological reporting capability.

The basic requirements of an optimization system are:

- This system shall command reporting “off” on some aircraft and command reporting “on” for certain aircraft based on an aircraft’s departure or destination airport and scheduled or estimated time of departure or arrival.

- The system shall command reporting “on” for the ascent, descent, or en-route phase of flight or for more than one phase of flight.

- The system shall accept a pre-planned schedule for an entire day and accept changes to the pre-planned schedule as often as once per hour in order to respond to rapidly changing requirements for meteorological data.

- The optimization system shall accept flight schedules from participating airlines and match an airline’s flight number to an aircraft tail number in order to send commands to the correct aircraft.

- The system shall accept a change if the airline substitutes an aircraft for one previously scheduled for a flight.

- The system shall treat flights from airports within a region such as Los Angeles (LAX, SAN, ONT, BUR), New York (LGA, JFK, EWR) or San Francisco (SFO, OAK, SMF, SJC) and other similar areas as terminal areas rather than individual airports.

- The system shall be capable of commanding reporting from all aircraft for a period of time in order to collect baseline quality or calibration data.

- The system shall be capable of assigning higher priority to aircraft with preferred reporting capabilities, such as water vapor, turbulence events and icing conditions, as well as aircraft that that provide more accurate measurements.

- The system shall be able to give priority to aircraft that conform to the ARINC 620 standard.

- Aircraft reporting shall be determined by a government representative based on the needs of the government for meteorological data; however, an airline shall also be able to establish reporting requirements for its aircraft in excess of the government's requirements.

- Depending on an airline's preference, the system shall be able to:
  a. Send commands directly from the data link service provider to aircraft or,
  b. Send commands to an airline host system to be forwarded by the airline to its aircraft.

4.2 Technical Interface

An optimization system could be implemented by adding a processor to store the required observations and aircraft characteristics, match flight number with aircraft tail number, and issue uplink messages. A workstation at NWS would enable meteorologists to define the required observations and to make changes as conditions warrant.

Figure 5 shows the MDCRS/AMDAR system architecture with the additional functional elements required for the Optimization System. The NWS reporting requirements would be converted to uplink messages by the optimization system processor. The resulting uplink messages would be sent to aircraft by one of two means; (1) directly from the optimization system processor through the ACARS Central Processor to the aircraft, or (2) from the optimization system process to the airline host computer, where the message would be verified, then back through the ARINC Data Network Service to the ACARS Central Processor and to the aircraft. When the uplink message is received by the aircraft it would change the aircraft reporting configuration to satisfy the reporting requirements. No other changes to aircraft systems would occur.

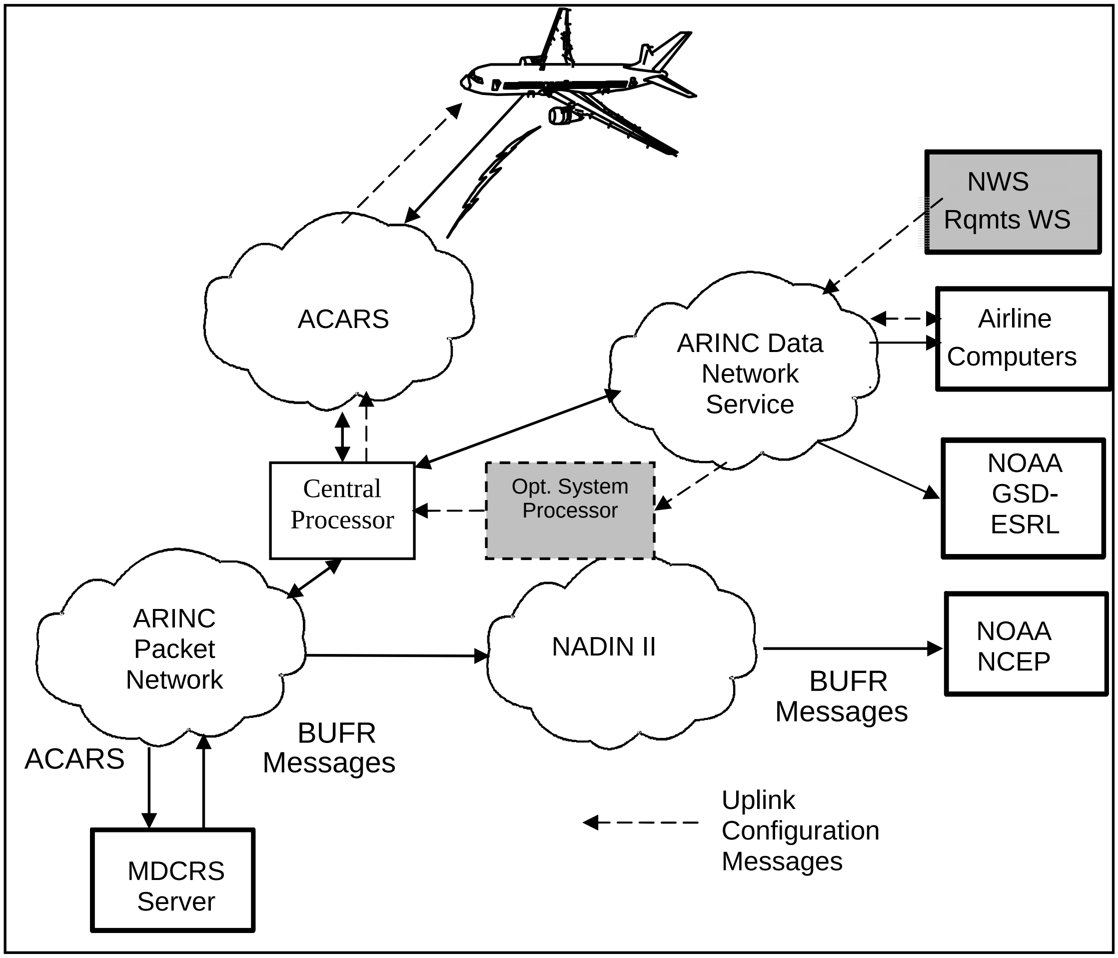

Figure 5. MDCRS Architecture with Optimization System

4.3 Benefits of an Optimization System

An optimization system would allow data to be collected from regions that are not well covered without substantially increasing the communications costs or the data link bandwidth required to transmit MDCRS/AMDAR messages.

More participating aircraft are necessary in order to increase the coverage of MDCRS/AMDAR. Although there are approximately 1,600 participating aircraft, there are at least that many of the same airframe types operated by U.S carriers that do not participate. Additionally, there are about 1,600 regional jets operated by regional airlines that could provide MDCRS/AMDAR data. Regional jets could be particularly valuable sources of weather observations since approximately half of their operations are from regional airports that are not served by the current MDCRS/AMDAR carriers. While additional aircraft represent opportunities to collect data in areas that are not well covered now, the number of data link messages associated with MDCRS/AMDAR could conceivably triple from its current state.

The major variable in the cost of providing MDCRS/AMDAR data is the cost of communicating the data link message from aircraft to the ground and from the ground processing center to

NOAA centers and airline operation centers. The current cost of communicating MDCRS/AMDAR data link messages is approximately $60K per month or $720K per year for about 2,500 soundings per day from 50 airports. Increasing the number of participating aircraft as described above could increase communication costs to about $180K per month or $2M per year.

For an approximation of the savings an optimization system could enable, consider the following scheme as a way to meet the NOAA requirement for observations.

- 2 soundings per hour for 18 hours (36 soundings per day) from 25 major airports
- 1 sounding per hour for 18 hours (18 soundings per day) from 15 airports
- 1 sounding every 2 hours for 18 hours (9 soundings per day) from 60 airports

This would provide a total of 1,710 soundings per day from 100 airports; a considerable increase in coverage with fewer soundings and lower communications cost than is the present case.

Another benefit of using an optimization system to manage the transmission of data is that the large number of redundant MDCRS/AMDAR data link messages would not be sent, thereby allowing the airlines to use more of their data link capacity for competing applications. Airlines choose how they will use their available data link capacity and how they will budget cost for data link applications; therefore, they are more likely to allocate a portion of their resources to MDCRS/AMDAR if fewer resources are required. This will become a more important consideration as data link usage expands as it has throughout its history and excess capacity shrinks.

5.0 Transition Plan

The Optimization System can be implemented in phases with an evaluation period as each phase is implemented before proceeding to the next phase. This approach will allow for an orderly development process and the refinement of technical requirements as the system proceeds to through each stage, with minimum cost and schedule risk. Four phases are envisioned.

5.1 Phase 1

Initially only one airline will be included in the optimization process to simplify the scheduling and coordination process.

Scheduling will be based on a current flight schedule for the duration of the evaluation period and will be fixed, with no capability for changing schedules.

Aircraft will be selected based on origination and destination airports with only ascent and descent phases of flight commanded “on”.

5.2 Phase 2

Phase 2 will add dynamic scheduling capability, the ability to change reporting schedules based on changing weather requirements.

5.3 Phase 3

The capability to optimize en-route reporting will be added, with the ability to select reporting aircraft based on their destination airport or route of flight and to command the interval between samples. Additional airlines will be included during this phase.

5.4 Phase 4

The ability to include in the aircraft selection criteria a factor for the quality of data received from that aircraft will be implemented.

6.0 Next Steps

1. Obtain acceptance of the requirements and the transition plan presented in this document by the stakeholders, including involved government agencies (NOAA and FAA), and airline industry participants. This could be facilitated by developing a presentation of the material in this document and meeting with government and industry stakeholders to obtain feedback.

2. The MDCRS/AMDAR service provider should develop a technical and cost proposal for the implementation of the Optimization System. The proposal would present an engineering solution, detailed implementation plan and schedule, and the cost of implementation.

3. After reviewing and accepting the proposal, the government would let a contract to develop and implement the Optimization System.

4. The performance of the system should be evaluated during the early stages of implementation and requirements should be adjusted and modifications incorporated as soon as possible.

References

Moninger, W. R., R. D. Manrosh, P. M Pauley. 2003: "Automated Meteorological Reports from Commercial Aircraft." Bulletin of the American Meteorological Society **84,** 203-216.

Moninger, W. R., S. G. Benjamin, D. Devenyi, B. D. Jamison, B. E. Schwartz, T. L. Smith, and E. Szoke. 2006: 10th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, 86th American Meteorological Society Annual Meeting, February 2006.

Helms, David, "Weather From the Cockpit." Regional Airline Association Flight Technology Conference, December 8, 2005, Ft. Lauderdale, FL

"Support for Automated Observations from U.S. Commercial Aircraft." Bulletin of the American Meteorological Society **84,** 515-517.

Appendix

A summary of the ARINC 620 meteorological report format is provided below.

(Note: OFF is the time that the airplane lifts off the runway and ON is the time the airplane touches down on the runway.)

- **ASCENT Reports**
  - Series #1:
    - Initial report at OFF.
    - Accumulate samples at intervals of 3 to 20 seconds. Default = 6 secs.
    - Stop at 30 to 200 secs. after OFF. Default = 90 secs.
  - Series #2:
    - Start at expiration of Series #1.
    - At intervals of 20 to 60 secs. Default = 20 secs.
    - Until 510 to 1110 secs. Default = 510 secs.
    - Transition to En-route at Top of Climb (TOC), 18,000 to 30,000 ft. Default = 25,000 ft.

- **EN-ROUTE Reports**
  - Series #1:
    - Begin at conclusion of Ascent reports.
    - 1 report = 6 consecutive samples
    - Intervals between Samples = 1 to 60 minutes. Default = 3 min.
    - Terminate when Descent report measurement begins.

- Ascent and Descent reports may be inhibited and only En-route reports generated beginning with OFF and ending with ON.

- **DESCENT Reports**
  - Series #1:
    - Report consists of 10 data samples over approx. 10 minutes.
    - Start at 18,000 to 30,000 ft., Top of Descent (TOD). Default = 25,000 ft.
    - Interval of data samples 20 to 300 secs. Default = 60 secs.
    - Final report at ON.

The two tables below convert typical ARINC 620 sample intervals to vertical and horizontal spacing. Table A-1 shows the vertical spacing between ARINC 620 sample intervals at typical rates of climb and descent. Actual rates of climb and descent can vary widely due to air traffic and weather conditions. Table A-2 shows horizontal spacing between ARINC 620 sample intervals during the en-route phase at 530 miles per hour, the nominal cruise speed for a Boeing 737, which is typical for large airframe aircraft. While aircraft characteristics will have some effect on the spacing between samples, winds at cruise altitudes and traffic conditions will have much greater effects.

For comparison, a weather balloon typically ascends about 1000 feet per minute and takes samples every 6 seconds or 100 feet at low altitudes and every 500 feet above 20,000 feet.

Sample Interval (sec)	Rate of Change (fpm)	Altitude Interval (ft)	Rate of Change (fpm)	Altitude Interval (ft)	Rate of Change (fpm)	Altitude Interval (ft)
Ascent Series 1						
3	2000	100	3000	150	4000	200
6	2000	200	3000	300	4000	400
10	2000	333	3000	500	4000	667
20	2000	667	3000	1000	4000	1333
Ascent Series 2						
20	1000	333	2000	667	3000	1000
30	1000	500	2000	1000	3000	1500
40	1000	667	2000	1333	3000	2000
60	1000	1000	2000	2000	3000	3000
Descent						
20	1000	333	2000	667	3000	1000
40	1000	667	2000	1333	3000	2000
60	1000	1000	2000	2000	3000	3000
120	1000	2000	2000	4000	3000	6000
180	1000	3000	2000	6000	3000	9000
240	1000	4000	2000	8000	3000	12000
300	1000	5000	2000	10000	3000	15000

Table A-1. Altitude between samples during ascent and descent

En-route Sample Interval (min)	Horizontal Spacing at 530 mph cruise speed, miles (km)
1	9 (14)
3	27 (43)
6	53 (85)
10	88 (142)
20	177 (285)

Table A-2. Horizontal spacing between samples during en-route phase