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REPORT ON TASK 1:

ASSESSMENT OF EXISTING DATA & REPORTS FOR SYSTEM EVALUATION

by

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NASA Glenn Weather Datalink Research
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Report on Task 1:
Assessment of Existing Data &Reports for System Evaluation

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Abstract

This report describes work done as part of the *Weather Datalink Research* project grant, number NAG3-2385. We describe the work done under Task 1 of this project: the assessment of the suitability of available reports and data for use in evaluation of candidate weather datalink systems, and the development of a performance parameter set for comparative system evaluation. It was found that existing data and reports are inadequate for a complete physical layer characterization, but that these reports provide a good foundation for system comparison. In addition, these reports also contain some information useful for evaluation at higher layers. The performance parameter list compiled can be viewed as near complete—additional investigations, both analytical/simulation and experimental, will likely result in additions and improvements to this list.

I. Introduction

In this report, we describe the results of our investigation regarding candidate datalink systems for use in the dissemination of weather information in the future civil aviation environment. This report addresses the first of two tasks under this project: the project is entitled *Weather Datalink Research,* grant NAG3-2385. The first task, denoted Task 1, was aimed at characterization of the datalinks through the use of existing data and reports. The goal was to make use of available *experimental* data, in contrast to studies that have relied primarily on analysis and system design descriptions. Task 2 was aimed at an experimental characterization of one candidate system: Very High Frequency Digital Link Mode 2 (VDLM2) via bench and flight testing. Task 1 has been divided into two subtasks as follows:

(1) Assessment of the applicability of existing data and reports for performance evaluation of potential systems for weather datalinks. An example set of data is the Safe Flight (SF) 21 Ohio Valley (OV) Automatic Dependent Surveillance-Broadcast (ADS-B) test data [1]. This assessment would aim at the future task of sorting and processing the data in a fair, comparative evaluation.
(2) Development of a set of comprehensive performance parameters to use in the evaluation.

Clearly the two subtasks must be done in conjunction with each other. In addition, the second subtask is closely related to Task 2 of the *Weather Datalink Research* project, which is the experimental evaluation of a candidate datalink system, namely, VDLM2.

The candidate datalink systems considered in this report are radio systems that provide communications connectivity between aircraft and ground sites, and potentially between aircraft in air-to-air situations. These systems are sometimes known as "RF" systems or simply, radios. These systems are terrestrially-based systems that do not include any satellite components explicitly [2]. The systems that we consider are listed in Table 1. Note that only the first three systems listed in Table 1were evaluated in any detail. We limited our investigation to these three systems because of the few resources that contained actual experimental data. These first three systems listed in Table 1 are candidate systems for use in Automatic Dependent Surveillance—Broadcast (ADS-B), and the experimental data we have was primarily data taken to evaluate this service.

Table 1. Candidate Datalink Systems Considered for Weather Datalinks.

System	Primary System Developer	Comments	Spectrum Currently Available ?	MOPS/ MASPS? (in process or under development)
Very High Frequency Digital Link (VDL) Mode 4 (VDLM4)	Swedish CAA	Regulatory challenges for US acceptance.	Yes	Yes
Universal Access Transceiver (UAT)	MITRE	Being used in FAA Capstone (ADS-B) project .	No	No (may be initiated soon)
Mode-S Squitter (MSSq)	MIT Lincoln Laboratory	Communications is secondary to radar functions, thus limiting data capacity	Yes	Yes
ArNav	Arnav	Will use VDLM2 in the future.	Yes	No
NavRadio	NavRadio (now Honeywell)		Yes	No
VDLM2	ARINC	Currently beginning deployment.	Yes	Yes
VDLM3	MITRE	FAA choice for digital voice.	Yes	Yes

The column heading "Spectrum Available?" refers to the current status of frequency allocation for the given systems. The column heading "MOPS/MASPS" refers to the presence or absence of current standardization efforts.

All evaluations were aimed primarily at physical layer (PHY) processes, algorithms, and hardware/software designs. Yet, even in modern communication systems that ascribe to the partitioned International Standards Organization (ISO) seven-layer protocol stack, characterizations of interest often cross layer boundaries, so that some evaluations will necessarily concern aspects at the datalink control (DLC) and medium access control (MAC) sublayers.

One aim behind subtask 1 was to make use of existing data, and avoid duplication of efforts. Another was to ascertain the presence of any gaps in system characterizations. These gaps could be the subject of future investigations. Additional benefits that arose from the subtask were the assimilation of a large body of knowledge regarding the candidate systems and their potential, and the development of relationships with key personnel and organizations involved in the candidate system analysis, design, development, and standardization. Finally, investigation of the candidate systems gave us a better understanding of the overall requirements for weather dissemination in the future National Airspace System (NAS).

The second subtask required a "fresh look" at the systems from a physical layer communications perspective, and as noted, closely corresponds to the planning and conduct of the experimental evaluations planned for Task 2.

In Table 2, we provide a summary of some features, parameters, and characteristics of the three systems for which the most information was available via the ADS-B system development. This table can serve as an overview of these systems. Inclusion of additional candidate systems is planned as more information is gathered.

Throughout the course of this investigation, we determined that the biggest gaps in information appear to be detailed physical layer characterizations of the candidate systems. The information listed in Table 2 is primarily system design information. It *enables* performance estimation, either by analysis or by computer simulation or both, but does not *provide* such performance results itself. In addition, in all cases, final performance results will depend not only upon the waveform, or "signal-in-space", which ultimately specifies the system transmitter, but also upon the *receiver* design choices. Some of this type of detailed information is proprietary to the system developers and its accessibility is currently being pursued. Other detailed physical layer characterizations, for example, the performance of each system in the presence of specified multipath distortion, must either use simulations, or simulations combined with analysis.

All this of course applies to the system designs which are of primary interest in this work and not the actual implementations. We found only one source in which experimental data was accurate enough to deem worthy of use: Johns Hopkins University Applied Physics Laboratory (JHU-APL). The JHU-APL data we obtained was test data taken to characterize physical layer performance in order to provide inputs to their datalink layer simulations for assessment of candidate systems for use in ADS-B. Thus, even this characterization is incomplete. These and all the other results are discussed subsequently.

In Section II, we first provide a description and initial results for subtask 2: the development of the set of performance parameters for comparative evaluation. Discussion of subtask 1 then follows in Section III. This discussion has direct impact on the first parameter set devised in Section II, so we then review subtask 2 as the final part of this report in Section IV.

Table 2. Summary Parameter & Feature List for the Three ADS-B Candidate Datalinks.

Parameter	MSSq	VDLM4	UAT
Frequency Band	1090 MHz	108-137 MHz	960 – 1215 MHz
# Channels	1	2 signaling (global) + 1 or 2 local	1
Approximate Channel Bandwidth (90% power)	$3.2R_b$	$1.2R_b$	$1.4R_b$
Multiple Access (MA)	random time (~ALOHA)	"S"-TDMA	TD (~S-ALOHA)
Channel R_b (kbps)	1000	19.2	1004.167
Minimum total frequency band for operation	~ 2 MHz (1 channel)	~ 75 kHz (2 signaling +1 traffic channels) × 25 kHz per channel	~ 2 MHz (1 channel)
Duplex method	Time/Half-duplex	Time: configurable up/downlink slots	Time: dedicated uplink/downlink slots
Minimum up/downlink frequency separation	0	0	0
Frequency planning requirements (re-use)	Unknown: likely a re-use factor of at least 7	Unknown: likely a re-use factor of at least 7	Unknown: likely a re-use factor of at least 7
RF channel spacing	~ 2 MHz	~ 25 kHz	~ 2 MHz
Spectral Efficiency (bps/Hz)	0.313	0.833	0.714
Max. User R_b (kbps) per timeslot	733.333 (counting user address as data) 533.333 (not counting user address as data)	13.2 (counting user address as data) 11.175 (not counting user address as data)	Air: 701.75 Ground: 921.51 (Both counting user address as data)
Multi-User Capacity: contention effect on overall R_b	Degrade by 82% (multiply by 0.18) for MA (ALOHA) & by more for radar	Degrade by 82% (multiply by 0.18) for MA (ALOHA), until "self-organized," at which point no additional users admitted & no contention	Degrade by 64% (multiply by 0.36) for MA (S-ALOHA)
Modulation	Binary PPM (binary orthogonal)	Binary GFSK h=0.25, $\Delta f = hR_b$ = 4.8 kHz (~6? kHz in practice)	Binary CPFSK h=0.6, $\Delta f = hR_b$ = 625 kHz (900 kHz in practice)
Frame time	NA: Timeslot is 120 μs	1 minute	1 second
# Timeslots/frame	1	4500	4000
Synchronization Sequence	4-bit (8μs) preamble	40 bit preamble	36 bit preamble

Parameter	MSSq	VDLM4	UAT
FEC Method	None	None	Shortenend RS
Error Detection (P_{undet})	24 bit parity (6×10^{-8})	16 bit parity (1.5×10^{-5})	24-bit CRC (6×10^{-8})
% overhead/slot	26.7(counting user address as data) 46.7(not counting user address as data)	15.7(counting user address as data) 25 (not counting user address as data)	31 (counting user address as data)
Total Bits/message (1 message/slot)	112	192	372
Proposed P_t (dBm)	48.5 – 57	34 – 47	40 – 48
Receiver Sensitivity (designed, for $P_{message} = 0.1$)	≤ -84 dBm, "high-end" Rx ≤ -74 dBm, "low-end" Rx	Not specified; characterization given as -103 dBm @ BER = 10^{-4}	≤ -92 dBm
Multipath mitigation	None	None	None
Interference mitigation	None	None	None
Complexity	Low	Medium/High	Low
Adaptability **Variable R_b?** **Power control?** **Variable f_c?**	 No No No	 No No No	 No No No
Security measures?	None	None	None
Handoff capability?	None	None	None
Expandability **New channels** **New "cells"** **Use of adaptive antennas**	 Yes ? ?	 Yes ? ?	 Yes ? ?
Integration?	Good where Mode-S transponders extant	May be capable of using existing VHF antenna	If in 980MHz band, new antenna may be required

II. Performance Parameters Used for Candidate System Evaluation

We note again that we have focused this set of performance parameters on the physical layer, but that inevitable intersections with DLC and MAC sublayers arose. The performance parameter list was originally conceived as a "wish list," in that we listed as many parameters and characteristics that we thought we would, ideally, like to have for comparisons among systems. (As the investigation progressed, this list expanded further.) In a later section of this report we provide another version of the parameter set that constitutes a version closer to a final one. We note that this second list may not ultimately be the final one, since information is continuing to be gathered, and since additional insight is gained from the experimental investigations of Task 2. We provide both of these lists in order to illustrate the evolution of understanding regarding the systems, and to indicate what a comprehensive characterization would contain.

In deriving the initial performance parameter set, we relied first on traditional measures of system performance such as bit error ratio (BER) versus signal-to-noise ratio (SNR). These are quantifiable measures, but they do still require precise definition. For example, the BER may be that of a particular message block, before or after error correction/detection; and, the point in the receiver chain at which the SNR is defined must be precisely specified. Nonetheless, these types of measures and characteristics are well understood and provide a foundation for experimental tests and equipment evaluations. We also obtained some performance parameters directly from the many references we consulted throughout the effort on Task 1.

In contrast to these quantitative PHY types of characteristics and parameters, there are those that are of a more qualitative nature. One example is technical maturity. These qualitative characteristics are of vital importance, but can be evaluated with less precision than the quantitative parameters.

Also of importance in devising the parameter set, and in Task 2, is the review of the *requirements* of the datalinks. These requirements are available in several sources, and apply to various levels of system design. From a broad communications perspective, some characteristics that are nearly universally desirable are the following:

- Message integrity: low probability of error P_e, and very low *P(undetected error)*
- Small latency: this depends upon the message priority as well as the PHY processing
- Low complexity: avionics must be inexpensive to gain wide acceptance, particularly in the case of general aviation
- Robust: primarily to in-aircraft/groundsite interference, and potentially multipath propagation

All these characteristics are rather high-level characteristics, and of limited use by themselves. They are though useful for classification purposes, and helped in the formation of the initial parameter set. The requirements for weather dissemination datalinks are laid out in [2]. In this report, and its accompanying database, some specific physical layer requirements are delineated, for a large number of different conditions (link type, phases of flight, type of aircraft, etc.). These requirements were gathered from a variety of sources, and encompass an enormous number of different message types and characteristics. (For example, 202 different message characteristics are listed in the database under the "Query Message Characteristics" option.) The mapping of requirements to datalink candidate systems was performed as part of this work [2]; an additional review of all these requirements and a comparison of them to the capabilities of candidate datalinks remains as a *significant* future task.

In Table 3 we present the initial performance parameter set. The column heading "Measurable?" refers to whether or not the parameter or characteristic *can* be measured, not if measurement is simple, or even possible for a specific set of equipment. We note that a comparison according to this table would provide a "first-round" evaluation of the candidate systems, and it would likely raise additional questions and areas for investigation. As noted, we revisit this table subsequently, after a discussion of the sources of information in the next section.

Table 3. Initial Version of Performance Parameter Set.

Parameter or Characteristic	Qualitative (L) or Quantitative (#)	Layer	Measurable? (Y/N)	Comments
1. P_b vs. SNR	#	PHY	Y	P_b = bit error probability, available by analysis for some schemes. An estimate of P_b is BER.
2. P_b vs. Interference *Co-Channel (CCI)* *Adjacent Channel (ACI)* *(several types for each)*	 # #	 PHY PHY	 Y Y	Naturally, interference can take many forms. Most pertinent is interference of the forms typically seen in/near the system operating bands.
3. $P_{message}$ vs. SNR	#	PHY/DLC	Y	Often measured is the % messages correctly received, P_{mc}. $P_{message} = 1-P_{mc}/100$
4. P_{sync} vs. SNR	#	PHY	Y	P_{sync} = probability of achieving correct synchronization. There exist several levels of synchronization (carrier, bit, frame, etc.) for each system.
5. Bandwidth	#	PHY	Y	Several measures of bandwidth are relevant: *B(x% power)*, *B(-y dB)*, etc., with typical values of 90, 99 for *x* and 20, 30, 40 for *y*. Allocation of spectrum is most critical.
6. Out-of-band emissions, transients	#	PHY	Y	Out of band emissions are related to bandwidth and regulatory spectral masks. Transients can be characterized in both time and frequency domains.
7. RF Link: Noise Figure	#	PHY	Y?	This is a hardware parameter, specified by the equipment manufacturer.
8. RF Link: $P_{transmit}$	#	PHY	Y	This is a hardware parameter, specified by the equipment manufacturer, but also easily measured.
9. P_b vs. Multipath	#	PHY	Y	*NO* typical or worst-case channel multipath profiles exist. An area for research?

Parameter or Characteristic	Qualitative (L) or Quantitative (#)	Layer	Measurable? (Y/N)	Comments
10. R_b (bps, messages/s)	#	PHY/DLC /MAC	Y	PHY R_b is well-defined. DLC/MAC R_b must account for protocols, which may require several assumptions.
11. Rx Complexity *Detection (C/NC)* *Synchronization* *RF HW, BB proc* *Tech Maturity*	 L L, # L, #? L	 PHY PHY PHY PHY/DLC ...	 N N N N	Complexity can be quantified in some cases, e.g., BB processing complexity is quantifiable by required processor FLOPs.
12. Tx Complexity *Synchronization* *RF Tx Cost* *BB Proc*	 L L, (relative #) L, #?	 PHY PHY PHY	 N N N	Same comment as in Rx Complexity applies. RF Tx cost dominated by power amplifier cost, which increases with operating freq.
13. Capacity	L, #	PHY/DLC /MAC	PHY:Y, higher:?	For PHY, capacity is mostly quantifiable, but does require assumptions. System capacity requires that higher layer characteristics be incorporated.
14. Adaptability	L	PHY/DLC	N	Adaptability in terms of R_b, P_{Tx}, etc.
15. Security *AJ/A-spoof* *Diversity* *ARQ*	 L L, # L, #	 PHY PHY DLC/MAC	 N N N	Most candidate systems have not designed in security measures at PHY. Diversity & ARQ are more "integrity" than security techniques.
16. Spectrum Availability	L	PHY	N	Mostly a regulatory issue—often the hurdle of finding "new" spectrum drives technical choices.
17. Integration	L	PHY	N	Manufacturers will naturally design for ease of integration; adding antennas to aircraft is undesirable.

III. Findings from Existing Reports

In this section we summarize the findings from the majority of the sources we have consulted. We briefly describe what each source contains, and whether or not it is indirectly or directly useful for evaluating the candidate systems.

A. Ohio Valley Safe Flight 21 Test Data

This data was taken during "Operational Evaluation Phase I" for the ADS-B system candidates in July 1999 [1]. The flight tests were designed to evaluate the operational effectiveness of ADS-B, primarily for surveillance purposes. Thus, the test results do *not* specifically address the communications capabilities of the candidate systems.

Two compact disks (CDs) were provided from Johns Hopkins University–Applied Physics Laboratory. The first CD contained *html* files of the Ohio Valley (OV) ADS-B test data compiled and processed by JHU-APL. The second contained much (possibly all) of the "raw data" that was recorded from ADS-B transmissions during the day of SF 21 testing.

The first CD contains different types of graphics for both UAT and MSSq:

- Plots of the plan view of the area, showing main cities, and/or local flight paths of most aircraft involved in the tests,
- MASP histograms for the time between received ADS-B updates at a specific receiver for targets (transmitters) in a specific range category. The histogram domains range from 0 seconds to approximately 3.6 seconds. These histograms essentially provide an empirical probability density function for the time between received ADS-B updates,
- Percent of messages received correctly vs. range, with altitude a parameter,
- Range versus time plots.

The graphics are available for up to twenty-five aircraft, many of which flew during all three sessions (morning, afternoon, and evening).

For the OV tests, only UAT and MSSq data were taken; the VDLM4 systems present were inoperable due to interface problems between radios and radio control devices. The type and accuracy of the data varies slightly between the UAT and MSSq systems. As an example, the "raw data" taken for MSSq included items listed in Table 4. This data is that logged at an aircraft receiver.

Table 4. Recorded Data and Descriptions for OV Flight Tests of Mode-S Squitter.[1]

Data Recorded	Description
Rec #	number (i.e., count) of the recorded message
ICAO Address	unique identifier for the transmitting aircraft
Updated Flags	??
Latitude	Latitude of transmitting aircraft according to ADS-B message
Longitude	Longitude of transmitting aircraft according to ADS-B message
Altitude	Altitude of transmitting aircraft according to ADS-B message
NSVelocity	North-South transmitting aircraft velocity according to ADS-B message
EWVelocity	EastWest transmitting aircraft velocity according to ADS-B message
SigLevel	Signal level as estimated via the receiver
MsgCount	aircraft-specific counter for messages sent
ErrCorrectCount	measure of message integrity, via error detection algorithm
ShrtSquittCount	??
TimeStamp	Time the message was sent, as per GPS at the transmitting aircraft ??
GPSTime(1999-07-10)	Time the message was received, as per GPS at the receiving aircraft

For our purposes in evaluating some of the physical layer characteristics described in Table 3, this data is inadequate. As an example, to assess the very first characteristic in Table 3, P_b versus *SNR*, we would need more error rate information than is provided by the "ErrCorrectCount" data recorded. This is because first, this indicator applies to message errors, and not bit errors; and second, the *SNR* values available are not sufficiently precise. (We could translate from bit errors to message errors, but this would likely involve bounds (inequalities) and not exact equations.) Instead of bit error probabilities, the recorded data on message errors could of course be used in message error probability characterization, as in characteristic number 3 of Table 3. Yet additional information is still required, namely that of accurate *SNR* values. The recorded "SigLevel" is only a rather coarse estimate of the received signal power—its accuracy is not known by JHU-APL, and for UAT, was not calibrated for the SF 21 tests [3]. Another means of determining this received signal power is via a link budget, but there are gaps in the data in regard to constructing an accurate link budget. To illustrate this, we provide a simple link budget description.

The digital version of *SNR* is the ratio E_b/N_0, where E_b = energy per bit, and N_0 = effective noise spectral density. A better term for the noise density of interest is actually $N_{0,eff}$, the effective noise density that accounts for excess receiver and external noise in addition to pure thermal noise. We have $E_b = p_r/R_b$, where p_r is the received power and R_b is the bit rate in bps. In dB,

$$E_{b,dBx/Hz} = P_{r,dBx} - R_{b,dB-Hz} \tag{1}$$

where the x subscript denotes the absolute power units being used, e.g., m for dBm, W for dBW, and $R_{b,dB-Hz} = 10\log_{10}(R_b)$. The effective noise spectral density $N_{0,eff} = kTf_n$, where $kT=N_0$ is equal to the thermal noise density (k is Boltzmann's constant and T is the receiver noise

[1] Note: Two of the rows in column 2 are lacking entries. After repeated contacts, we were unable to obtain any information from MIT Lincoln Laboratory regarding Mode-S Squitter and the SF 21 testing.

temperature, typically taken as room temperature of 290 K), and f_n is the receiver noise figure. Thus in dB,

$$N_{0eff,dBx/Hz} = N_{0,dBx/Hz} + F_{n,dB}\,, \tag{2}$$

with $F_{n,dB} = 10log_{10}(f_n)$. (Note that f_n should account for both receiver and external noise.) Combining equations (1) and (2) yields an expression for the SNR E_b/N_0,

$$(E_b / N_0)_{dB} = P_{r,dBx} - R_{b,dB-Hz} - N_{0,dBx/Hz} - F_{n,dB}\,. \tag{3}$$

Since we do not have a precise value for received power, to complete the link analysis requires an expression for received power given transmitter power, channel gain, and some additional parameters. The received power is computed as follows:

$$P_{r,dBx} = P_{t,dBx} + G_{t,dB} - L_{fs,dB} - L_{ex,dB} + G_{r,dB}\,, \tag{4}$$

where the quantities in (4) are defined as

$P_{t,dBx}$ = transmitted power in dBx
$G_{t,dB}$ = transmit antenna gain in dB
$L_{fs,dB}$ = free-space path loss, dB, equal to $20log_{10}(4\pi d/\lambda)$, with d = distance, λ = wavelength
$L_{ex,dB}$ = excess loss, dB, due to atmospheric effects such as absorption, scattering, etc., and to electromagnetic propagation effects such as multipath propagation and diffraction
$G_{r,dB}$ = receive antenna gain in dB

[Note: Accounting for the propagation component of $L_{ex,dB}$ requires additional calculations to determine elevation angle and potentially terrain diffraction in specific cases. The approximate values of this propagation component can exceed 20 dB, which is an unacceptably large value for accurate link calculations if unknown.]

Combining (3) and (4) yields the desired result:

$$(E_b / N_0)_{dB} = P_{t,dBx} + G_{t,dB} - L_{fs,dB} - L_{ex,dB} + G_{r,dB} - R_{b,dB-Hz} - N_{0,dBx/Hz} - F_{n,dB}\,. \tag{5}$$

We address the terms in (5) one at a time. First, the terms for which we have good estimates:

- The transmit power $P_{t,dBx}$, while not explicitly listed in the data recorded, should be obtainable. It was constant for each transmitter used in the SF 21 tests.
- From the data recorded in Table 3, we can compute the quantity $L_{fs,dB}$ with good accuracy from the latitude/longitude/altitude information, combined with the same type of information from the receiving aircraft. Since this information was derived from GPS, even GPS errors on the order of 100 m (95% confidence level) translate to negligible effects (fractions of a dB) on $L_{fs,dB}$ when distances between aircraft are beyond a few kilometers.
- For VHF and UHF frequencies, the excess loss $L_{ex,dB}$ due to atmospheric effects is negligible, but the loss due to propagation effects can be *significant*, as noted. These effects are typically time-invariant, and deterministic, but must be accounted for in each

case (for each link). This was *not* explicitly done for the SF 21 tests, and so the propagation component could only be estimated, with questionable accuracy.

- We know $R_{b,dB\text{-}Hz}$ for each system.
- We know $N_{0,dBx/Hz}$ for each system.

The quantities that we do not have are the following:

- Transmit antenna gain $G_{t,dB}$
- Receive antenna gain $G_{r,dB}$
- Receiver noise figure $F_{n,dB}$.

The antenna gains have "typical" values, but these values vary considerably (several dB) with aircraft orientation, and this effect was *not* accounted for in the recorded data. Note that for ADS-B evaluations, antenna gains are planning to be modeled as Gaussian (or truncated Gaussian) random variables for any given orientation [4], with a (mean,variance) to be determined. (Tentatively, a standard deviation of $\sigma \cong 3$ dB was proposed.) Noise figures for the receivers alone might be available from manufacturer specifications, but the on-board "excess" noise external to the receiver is not known. Without these quantities, accurate assessments of the signal to noise ratio E_b/N_0, and hence its relation with error probabilities, simply cannot be made.

Similarly, many of the other PHY characteristics of Table 3 cannot be accurately determined from the OV data. (We note that data taken by Ohio University during the SF 21 tests is also available, and represents a subset of the JHU-APL data. The OU data is of the same form as the JHU-APL data and hence has the same shortcomings.) Some assessments of the more qualitative characteristics may be able to make use of this data, but these characteristics (e.g., receiver complexity) are more easily addressed using other information contained in other sources. These sources are the subject of the remainder of this section.

B. NASA Glenn Advanced Air Transportation Technologies (AATT) Task Order 24 Report

This report [2] is an in-depth review of candidate datalink systems for weather dissemination, at a "system" level. It is a thorough analysis of the requirements and relationships among systems for two target dates: years 2007 and 2015. It contains no actual test data or results. Thus, it will not provide information to characterize the systems according to all the measures in Table 2. The summaries of candidate datalink systems included in this report have been used in comparing parameters and features of the systems, as in Table 2, and will be of use in helping evaluate some of the qualitative performance measures.

C. Operational Evaluation Coordination Group, Phase—I Operational Evaluation Final Report

This report [5] contains a reasonably detailed summary of the SF 21 ADS-B testing from July 1999. It made use of the same data as discussed in subsection *A* above, and in addition collected survey data from test participants (pilots, controllers) for assessing various human factors aspects of ADS-B effectiveness.

The goal of this evaluation was much broader than that of a simple assessment of the performance of the various links. Flight crews were observed by trained observers. These observers gathered information used in assessing the usefulness of ADS-B, for example in its ability to enhance visual "see and avoid" procedures. Controllers were also observed by trained observers. Evaluations of the effectiveness of Cockpit Display of Traffic Information (CDTI) were gathered from questionnaires and voice tapes. The report also evaluates other systems such as radar tracking systems.

Datalink analysis in this report is minimal. The report actually refers to the data collected by JHU-APL (see subsection *A* above). Mention is also made of simulations used to assess performance. The report describes development of link simulations in conjunction with bench and flight tests, and notes that "The data give an indication of Extended Squitter and UAT message error rate performance versus range for some specific scenarios/aircraft geometries and background noise environments." Naturally the test results can be used to validate the simulations, and this is in fact planned. From communications with one of the JHU-APL test engineers [6], we have found that the characterization of the candidate system link performance at the physical layer is incomplete, and will serve mainly to provide inputs to a DLC layer simulation. The report notes that the datalink evaluation being done at JHU-APL is scheduled for completion in December 2000. The report also refers to an interim report of the ADS-B Link Evaluation Team, which is discussed in the next subsection.

D. Safe Flight 21 Technical/Certification Subgroup, ADS-B Link Evaluation Team, Phase One Link Evaluation Report; Status and Initial Findings

This document [7] contains descriptions of the three ADS-B candidate systems: UAT, Mode-S Squitter, and VDLM4. The descriptions are detailed, and address the PHY, DLC, MAC, and sometimes higher layers. Many system parameters are also often provided. The ADS-B Link Evaluation Team based its evaluation on a set of technical performance criteria, derived from several sources (e.g., RTCA MASPS). Some of these performance criteria are relative, in that systems are compared with one another, not via a quantitative measure. An example is the ability of the system to enhance visual operations and situational awareness. Nonetheless, this document represents one of the most useful documents found for understanding the operation of each system.

Some of the evaluation parameters of Table 2 were obtained from this document. An example is RF transmit power. The transmit power for most systems has a range of values, and these values may apply specifically to the radio equipment used for the SF 21 evaluation, but the values are still of use in estimating coverage range. Other parameters such as bandwidth measures, data rate, and qualitative ratings such as complexity were also obtained from this document. As with many other reports though, this document contains no experimental test data.

E. Johns Hopkins University Applied Physics Laboratory, UAT Lab Testing: LDPU Radios; Results

This document [8] is a short presentation from Johns Hopkins University's Applied Physics Laboratory. A summary of some test results for two UAT transceivers is given. The test results provided are sample results from laboratory testing in the presence of noise and interference. These results are some of the most useful results we have found; they could form a portion of an in-depth report on the UAT system, as they contain measured values of such characteristics as message error rate vs. SNR and SIR.

F. Johns Hopkins University Applied Physics Laboratory, 1090 Receiver Testing: LDPU

This document [9] is another short presentation from Johns Hopkins University's Applied Physics Laboratory. As in the document in subsection *E* above, this is also a summary of some test results for MSSq transceivers. The test results are sample results from laboratory testing in the presence of noise and interference, and as with the UAT results, could form a portion of an in-depth report on the MSSq system.

G. FAA NAS 4.0 Architecture Description

The FAA's NAS Architecture Description report [10] is a broad overview of the requirements and desires for the future National Airspace System (NAS). Its focus is not only communications, but also navigation, surveillance, avionics, traffic flow management, flight services, infrastructure management, and equipment modernization. It is thus not a source from which detailed information regarding communication technologies will be obtained.

Its description of the communication system evolution is pertinent to the evaluation of candidate aviation weather datalinks. The document provides useful information regarding the *planned* dates of the various communications upgrades, and how future communication services will work together.

H. RTCA SC 195 Minimum Aviation System Performance Standards (MASPS) for Flight Information Services--Broadcast (FIS-B) Datalink

This document [11] is a draft standard that contains requirements for broadcast flight information services (FIS-B). It provides a set of requirements against which the candidate link systems can be measured, at the DLC sublayer. *No* physical layer requirements are included. Also included are recommended standards for the airborne processing and display of FIS-B information, and procedures for performance requirement verification.

I. Capstone Proposed Initial Draft Standard for UAT

This draft standard [12] provides a good description of the operational principles behind the UAT system. It gives a modest amount of information on the physical layer parameters of the UAT waveform and signaling scheme. Some of this information is also contained in the Safe Flight 21 ADS-B Link Evaluation Report [7]. As with that report, some PHY parameters are specified, and this draft standard could thus be of some use in completing a table similar to Table 2.

J. DRAFT of Manual on Detailed Technical Specifications for the VDL Mode 4 Datalink

This draft specification [13] provides mostly DLC and MAC layer descriptions for the VDLM4 system. In addition, VDLM4 uses two additional sublayers in layer 2: the VDLM4

Specific Services (VSS) sublayer, which provides communications using a flexible burst format and associated transmission and reservation protocols over the MAC sublayer; and the Link Management Entity (LME), which establishes and maintains connections. The DLC sublayer is also modified to be a datalink services (DLS) layer. No physical layer information is presented. The draft specification may be useful for evaluating the layer two design of VDLM4 when the layer one evaluation is complete.

K. VDL Mode 4 Validation Report

This report [14] is a fairly high-level description of the activities in the VDLM4 Validation Subgroup of AMCP. It provides information regarding the validation of various VDLM4 functions and requirements, and the AMCP schedule.

L. VDL Mode 4 System Description

This set of documents [15] contains a description of the VDLM4 system, for use in the SF 21 ADS-B link evaluation. Most of the material is the same as that contained in the Safe Flight 21 ADS-B Link Evaluation Report [7].

M. Test Results of the Aviation Data System Innovations (ADSI) LLC VDL Mode 4 Equipment for ADS-B Applications in the Upper VOR Band

This report contains the test results of the Aviation Data System Innovations (ADSI) Limited Liability Company VDL Mode 4 Equipment as tested at Ohio University Avionics Engineering Center. The purpose of the tests was to provide spectral compatibility data to assess the feasibility of frequency assignments; in particular, the tests aimed to ascertain the suitability of assigning VDLM4 ADS-B services to the upper VHF Omnirange (112 – 117.95 MHz) band. The test results include sample transmit spectra, receiver sensitivities, and performance tests in the presence of adjacent and co-channel interference. Thus, these results could form a portion of an in-depth report on the VDLM4 system.

IV. Performance Parameters for Evaluation

In Table 5, we present the set of performance parameters we propose for evaluation. The table is an *expanded* version of Table 3, but the number of parameters we denote as measurable is *smaller* than the number in Table 3. For clarity, the table rows that describe parameters or characteristics that are NOT measurable are shaded; the rows that describe parameters or characteristics that ARE measurable are left unshaded. We have also added a column with heading "Analyzable?" This designation refers to whether or not the quantity or characteristic in question can be derived from theoretical results, simulations/emulations, or other measured quantities. Note that entries in the "Comments" column are different from those in the corresponding location in Table 3.

Table 5. Current Version of Performance Parameter Set.

Parameter or Characteristic	Qualitative (L) or Quantitative (#)	Layer	Measurable? (Y/N)	Analyzable? (Y/N)	Comments
1. P_b vs. SNR	#	PHY	N	Y	This can be computed approximately from message error probabilities. For a given modulation scheme, it can also be computed for uncoded symbols. Translation to coded symbol error rates can be done using specific FEC code parameters. This translated P_b can then be compared with that computed from message error probabilities.
2. P_b vs. Interference *CCI* *ACI*	 # #	 PHY PHY	 N N	Y	As with *#1, P_b vs. SNR*, this can be estimated from message probabilities. CCI will be same-system, processed (scaled, delayed, etc.) as appropriate; ACI will also be same-system, but in addition may be signals from systems in adjacent bands (e.g., FM broadcast).
3. P_m vs. Interference *CCI* *ACI*	 # #	 PHY PHY	 Y Y	?	$P_m = P_{message}$. An analysis of message error probability would require knowledge of channel effects (correlations) over blocks of messages. This may or may not be obtainable. Regarding the interferences, the same comments as in #2 apply. For UAT and MSSq, some measured results available from JHU-APL. Note that to be fair among different systems, messages must be of identical length.
4. $P_{message}$ vs. SNR	#	PHY/ DLC	Y	?	Comments similar to that in #3.
5. P_{sync} vs. SNR	#	PHY	N	N	P_{sync} = probability of achieving correct synchronization. Ideally, several levels of synchronization (carrier, bit, frame, etc.) tested. Synchronization loop performance is a direct function of SNR, but accurate analysis is not feasible, due to the nonlinear nature of the loops. Good approximations are possible, but detailed loop parameter data is required for these, and this data is unlikely to be available. Information on P_{sync} can be useful for understanding the mechanism behind message errors, but is likely not of interest at higher levels.

Parameter or Characteristic	Qualitative (L) or Quantitative (#)	Layer	Measurable? (Y/N)	Analyzable? (Y/N)	Comments
6. Bandwidth	#	PHY	Y	Y/N	Bandwidth for the linear modulation schemes (8PSK) can be analytically obtained, at least approximately. Precision in these analyses requires detailed data on transmitter filters. Bandwidths for the CPM schemes can be found by numerical techniques and/or simulations. For UAT, some measured results available from JHU-APL.
7. Out-of-band emissions, transients	#	PHY	Y	N	Transients, characterized in both time and frequency domains, will depend upon implementations. The analytical characterizations of transients are typically intractable. For UAT, some measured results available from JHU-APL.
8. RF Link: Noise Figure	#	PHY	Y	N	Noise figures can be measured, but the value in measurement is questionable, since external (to receiver) noise is often dominant. For UAT and MSSq, some measured estimates available from JHU-APL.
9. RF Link: $P_{transmit}$	#	PHY	Y	NA	For UAT, some measured results available from JHU-APL.
10. P_b *vs.* Multipath	#	PHY	N (possibly Y in future)	Y?	As previously noted, *NO* typical or worst-case channel multipath profiles exist. The effect of multipath echoes on transmissions near airports (during takeoff/landing) is largely unknown. The effect is cited several times in [7] as an area worthy of investigation. Once channel characteristics are obtained, performance for transmission schemes may be analyzed. (Note: The question mark after the "Y" under "Analyzable?" means that analysis is possible to some degree, i.e., analytical results may only be approximate.)
11. R_b (bps, messages/s)	#	PHY /DLC /MAC	PHY: Y DLC/MAC: ?	Y?	PHY R_b is measurable, and for the most part, is available from system design documents. DLC/MAC R_b must account for protocols, which may require several assumptions and may best be obtained via emulations and simulations. (Note: The question mark after the "Y" under "Analyzable?" means that analysis is possible to some degree, i.e., analytical results may only be approximate.)

Parameter or Characteristic	Qualitative (L) or Quantitative (#)	Layer	Measurable? (Y/N)	Analyzable? (Y/N)	Comments
12. Rx Complexity *Detection (C/NC)* *Synchronization* *RF HW, BB proc* *Tech Maturity*	 L L, # L, #? L	 PHY PHY PHY PHY /DLC…	 N N N N	 Y Y? Y Y?	Most of the analysis under receiver complexity will amount to quantifying processing requirements.
13. Tx Complexity *Synchronization* *RF Tx Cost* *BB Proc*	 L L, (relative #) L, #?	 PHY PHY PHY	 N N N	 Y? Y Y	Similar comments to #12. In addition, cost can be related to RF.
14. Capacity	L, #	PHY /DLC /MAC	PHY:Y, DLC/MAC: ?		For PHY, capacity is mostly quantifiable, but does require assumptions, in particular regarding re-use distances and S/I requirements. As with R_b, overall system capacity requires that higher layer characteristics be incorporated, and hence its assessment will likely require emulation and simulation.
15. Adaptability	L	PHY /DLC	N	Y	Requirements for adaptability of system parameters such as R_b, P_{Tx}, have not been made. System "flexibility" can be addressed somewhat qualitatively.
16. Security *AJ/A-spoof* *Diversity* *ARQ*	 L L, # L, #	 PHY PHY DLC /MAC	 N N N	 Y Y Y	Requirements on system security at the physical layer have not been made.
17. Spectrum Availability	L	PHY	N	Y	Concern primarily for UAT, but there are also transition issues for VDLM4 depending upon the communications/navigation distinction (functional separability) by regulatory bodies. Ultimately quantifiable (~measurable) as binary (yes/no) value.
18. Integration	L	PHY	N	Y	Can be crucial to cost, in particular if new antennas required.

V. Summary

In this report, we have described the results of our investigation into the characteristics of several datalink systems under consideration for use in the dissemination of weather information. This investigation was denoted Task 1 of the project entitled *Weather Datalink Research*, grant NAG3-2385. The goals of Task 1 were twofold: to investigate both the use of existing data and reports for system evaluation and, the generation of a performance parameter list for use in comparative system evaluations.

We found that the data that exists on the systems is incomplete and inadequate to perform a detailed assessment of the physical layer characteristics of the systems. The performance parameter list in its latest form is shown in Table 5. It will be updated as needed in the future based upon additional investigations, some of which will be experimental testing (Task 2 of this same project, and possibly future testing). What little usable data that exists comes from JHU-APL and their laboratory testing of ADS-B system candidates. This testing was made on only a few prototype units and thus may not represent a good statistical characterization.

This investigation revealed a significant gap in the description of all the systems: the lack of explicit physical layer characterizations via analysis, simulation, and testing. The physical layer characterizations that we did find were cursory and aimed primarily at providing inputs to higher layer simulations and analyses. No information on how the systems perform in comparison to theoretical expectations was found. (Note: *indications* of performance for some systems may lie in MOPS/MASPS as performance specifications, but even these indications will be incomplete, e.g., BER will often be specified at only one or two values of SNR instead of over a large range of SNR values.) Comparisons with theoretical results are of use in judging the soundness of the engineering implementations and also in lending insight into system operation. No information on simulated performance characteristics of the systems was found, but some of this is still being sought, as what exists appears to be proprietary.

As an example of an omission, one performance parameter that is essentially uncharacterized is the system performance (BER, MER) in the presence of multipath distortion. While this signaling impairment is mostly negligible for enroute high-altitude transmissions (except at low elevation angles), it can present a significant degradation to performance for other phases of flight (takeoff/landing), and while aircraft are in the terminal area on the ground. The neglect of this impairment was noted by the ADS-B link evaluation team as an area for future work [7]. Multipath characterization by this group will be very limited, due to time, budget, and equipment limitations [16].

Despite these concerns with the reports and data reviewed, considerable insight into candidate system operation was obtained from this investigation. It can also be stated that the system operational concepts are fairly mature, and that the waveform ("signal-in-space") designs are fairly traditional, and hence can be expected to lead to reliable links provided implementations are sound.

Future work that should be considered is described as follows:

1. Evaluation of the large number of system requirements for weather dissemination. This could constitute a review of the work in [2], as well as an independent review of the resources used in this work. Translating the high-level requirements into lower level datalink requirements could prove the biggest (but most important) challenge.
2. Completion of a table similar to Table 2 for the *remaining* systems listed in Table 1 as "NOT evaluated in this report"

3. Completion of a table similar to Table 3/Table 5 for *each* candidate system. This would likely require more than a table for each system, ideally as much as an in-depth report on each system. The report would consist of a system description; analytical, simulation, and experimental characterization at the physical layer; and inputs for future analyses and simulations (e.g., for datalink and higher layers), as well as recommendations regarding system suitability for weather dissemination.
4. Investigation of the "unmeasurable" system parameters/characteristics in Table 5. As with item 3 above, a thorough investigation could lead to detailed analysis and simulations. One aim here would be to "close the loop" and provide a consistency check on the other performance parameters. As an example, if the SNR required for good performance (in terms of low probability of message error) is less than that required for system synchronization, one of these characterizations must be in error.

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[7] Safe Flight 21 Technical/Certification Subgroup, ADS-B Link Evaluation Team, "Phase One Link Evaluation Report; Status and Initial Findings," November 1999.

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Appendix A: List of Relevant Contacts/Subject Matter Experts

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