RANGE SAFETY GROUP

SPECIAL REPORT

FLIGHT SAFETY SYSTEM (FSS) FOR UNMANNED AERIAL VEHICLE (UAV) OPERATION

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Prepared by

RANGE SAFETY GROUP (RSG)

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PREFACE

This document was prepared by the Range Safety Group (RSG), Range Commanders Council (RCC) under Task RS-39. The Group investigated options other than "destruct" for unmanned aerial vehicles (UAVs) flying in the National Airspace (NAS) over populated areas and outside the range of local line-of-sight (LOS) flight termination system (FTS) transmitters.

The objective of this document was to develop an RCC standard for over-the-horizon (OTH) safe recovery of UAVs. The task considered requirements for global monitoring of UAV critical safety information and implementation of hazard control options such as reset flight control computer, uplink new route, change altitude, and override controls for UAV safe-recovery operations.

The RCC gives special acknowledgement for production of this document to members of the RSG. Please direct any questions to the group's point of contact or to the RCC Secretariat as shown below.

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ACRONYMS AND ABBREVIATIONS

3-DES	Triple Data Encryption Standard
ACK-NAK	acquisition/no acquisition
AFFTC	Air Force Flight Test Center
ARINC	Aeronautical Radio, Inc
CRC	Cyclic Redundancy Checklists
FAA	Federal Aviation Administration
FTS	flight termination system
GEO	geo stationary earth orbit
LBT	L-Band Transceiver
LEO	low Earth orbit
MEO	medium Earth orbit
MTBF	mean time between failure
UAV	unmanned aerial vehicle
OTH	over-the-horizon
PSTN	public switched telephone network
RAFS	Robust Affordable Flight Safety
RSO	Range Safety Officer

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CHAPTER 1

RS-39 TASK REPORT

1.1 Introduction

Test ranges currently use simple, line-of-sight transmission systems to control errant Unmanned Aerial Vehicles (UAVs). Typically, this means placing the hazardous vehicles in a zero-lift, zero-thrust condition through some sort of destructive mechanism. These transmission systems or "Flight Termination Systems (FTSs)" work well for UAVs that remain within a certain distance of the FTS (or Command) transmitter, but fail to meet long-range, high-altitude UAV requirements. Additionally, these FTSs increase operational risk as they are susceptible to signal interference and the possibility of unauthorized users. The RS-39 task was established to investigate alternatives to traditional FTSs for use on UAVs flying over populated areas, outside range airspace, beyond line-of-sight, or that have demonstrated reliability making FTS undesirable or unnecessary but where additional controls are still warranted to mitigate risk.

1.2 Alternatives Considered for FTS

A wide variety of alternatives were examined during the RS-39 task. Key requirements consisted of global coverage, over-the-horizon (OTH) operation, data throughput rates, system complexity, and availability. Based on these requirements, alternatives were separated into two categories. The first category included terrestrial or land-based systems, and the second consisted of satellite based systems.

1.2.1 Terrestrial Systems. Terrestrial systems offer a number of benefits, but fail to support many critical requirements. For instance, the Federal Aviation Administration's (FAA's) Aeronautical Radio, Inc. (ARINC) communication network provides OTH coverage and good data throughput, but system complexity makes it impossible to interface with. Out of twenty-four terrestrial alternatives, only two showed promise and after further study even those fell short of providing the needed capabilities. As a result, the RS-39 task focused on satellite systems.

1.2.2 Satellite Systems. Satellite systems appear to be the obvious choice for long-range OTH applications since most provide near-global coverage. In addition, their digital infrastructures make it easy and cost-effective for ranges to connect them to their existing networks. Satellite systems are classified into three primary orbit types: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geo-stationary (synchronous) Earth Orbit (GEO). The RS-39 task found that MEO and GEO satellites incurred propagation delays which were unacceptably large for FTS use. As such, they were eliminated and researchers concentrated on LEO satellites.

a. LEO Satellites. LEO satellites are a good idea for more than just technical reasons. Industry has placed large financial investments into LEO satellites to upgrade their global communication networks. Ranges can leverage these investments to develop advanced FTS applications without worrying about lifecycle and mission assurance issues. The following table lists the possible LEO alternatives and whether or not they support the driving requirements.

TABLE 1-1. SATELLITE SELECTION MATRIX

	Status	Instantaneous Coverage	Latency	Throughput	Terminal Complexity	Antenna Complexity	STOP ✓
LEO messaging							
Orbcomm	Existing	35 satellites	S&F	Packet System	Simple VHF/UHF	omni antenna	STOP
VITAsat	Existing	2 satellites	S&F	Packet System	Simple VHF/UHF	omni antenna	STOP
LEO ONE	Planned	48 satellites	S&F	Packet System	Simple VHF/UHF	omni antenna	STOP
E-Sat	Planned	6 satellites	S&F	Packet System	Simple VHF/UHF	omni antenna	STOP
ARGOS	Existing	2 satellites	S&F	Packet System	Simple VHF/UHF	omni antenna	STOP
Aprize Satellite	Planned	48 satellites	S&F	Packet System	Simple VHF/UHF	omni antenna	STOP
SENS	Planned	2 satellites	S&F	Packet System	Simple VHF/UHF	omni antenna	STOP
FAISAT	Planned	26 satellites	S&F, RT?	Packet System	Simple VHF/UHF	omni antenna	STOP
LEO voice and data							
Globalstar	Existing	48 satellites	RT	9.6 kbps	Complex L Band	omni antenna	STOP
Iridium	Existing	66 satellites	RT	2.4 to 10 kbps	Complex L Band	omni antenna	✓
Teledesic	Planned	288 satellites	RT	2 to 64 mbps	Complex K band	unknown	STOP
Courier	Planned	72 satellites	RT	Unknown	Unknown	Unknown	STOP
MEO voice and data							
Ellipso	Planned	17 sats., phased	RT	28.8 kbps	Complex L,S Band	omni antenna	STOP
GPS block modifications	Future	global	RT	??	??	??	STOP
ECO-8	Existing	11 satellites	RT	9.6 kbps	Complex L Band	omni antenna	STOP
New ICO	Planned	12 sats	RT	144 kbps	Unknown	Unknown	STOP

Best, satisfies requirement, most confidence, easiest
Cautionary, may satisfy requirement, some confidence, some difficulty
Worst, does not satisfy requirement, least confidence, most difficult

RT Real Time
S&F Store and Forward

b. IRIDIUM Satellite System. A quick look at Table 1-1 reveals that many LEO satellites meet most requirements, but only IRIDIUM satisfies all of them. The IRIDIUM system is an existing network of 66 satellites designed to deliver reliable real-time voice, data, paging, and facsimile communications all over the planet. Full duplex data rates in excess of 2.4 kbps are supported. IRIDIUM uses a ‘switched’ architecture, ensuring true global coverage. Access is via a cell-phone like unit with omni-directional antenna or a data modem unit. Based on these findings, IRIDIUM was selected as the most feasible alternative.

1.3 Prototype FTS Built: Robust Affordable Flight Safety (RAFS) System

Since IRIDIUM was deemed most suitable, a prototype FTS was developed to validate the concept. The prototype was called the RAFS. Developed by Reliable System Services Corporation under contract to the Air Force Flight Test Center (AFFTC), the RAFS design leveraged expertise within the Range Commanders Council (RCC) Range Safety Group to ensure key FTS concerns were addressed and RCC 319 (Flight Termination Systems Commonality Standard) requirements were met. The result was a system that provided many enhanced capabilities while adhering to traditional FTS requirements.

In addition to an OTH capability, a key enhancement is the ability to receive vehicle and FTS health and status from UAVs. This enhancement is possible because the IRIDIUM system transmits data in both directions. The result is improved situational awareness independent of conventional telemetry systems. Figure 1-1 illustrates the RAFS system concept.

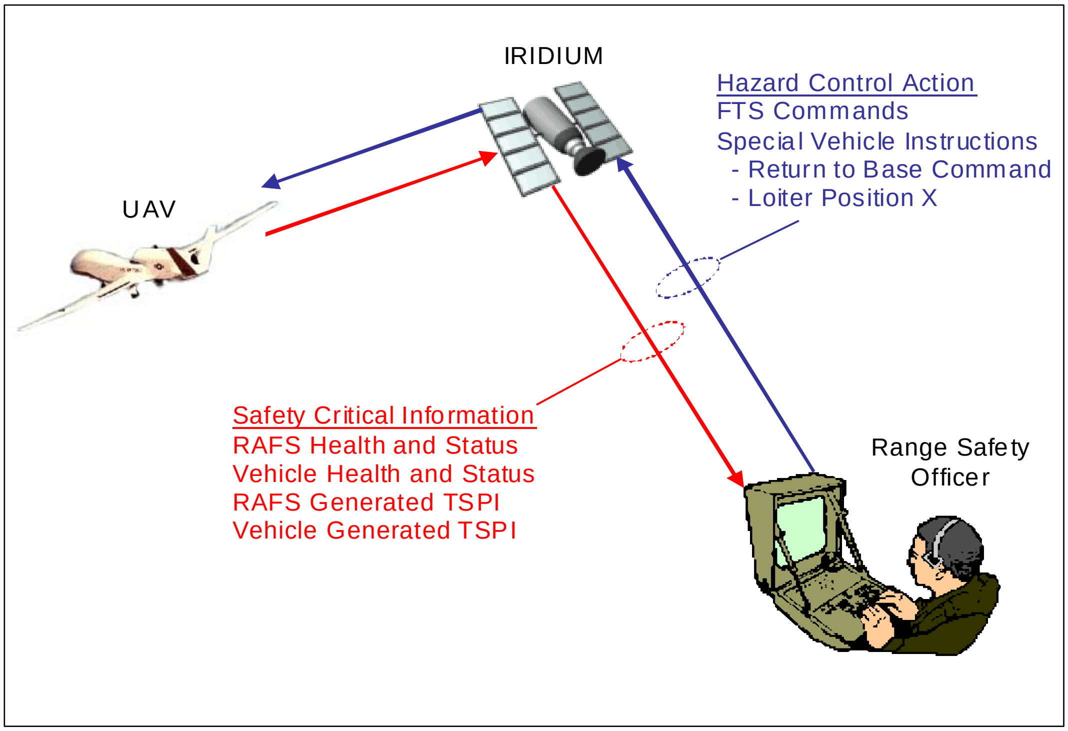

Figure 1-1. RAFS Concept.

The RAFS makes it possible to communicate with UAVs anywhere in the world. As Figure 1-1 shows, the Range Safety Officer (RSO) can monitor health and status parameters like engine performance and control system data. The RSO can also issue special commands for improved safety when flying outside restricted airspace. For example, an RSO can tell an errant vehicle to return to base or fly a specific pattern centered on predetermined coordinates until a solution to the problem is determined. This option is extremely attractive to projects that have established high vehicle reliability through actual flight test as it could eliminate the need for a traditional FTS.

The RAFS development was accomplished in two years and culminated in a successful flight demonstration. During the demonstration, engineers sent FTS and special vehicle commands from the RAFS ground station located at Edwards AFB, California, to a UAV flying over Patuxent River Naval Station, Maryland. The engineers were also able to monitor the vehicle and RAFS health and status parameters.

1.4 Prototype issues

Although the test and overall development effort was deemed successful, a few issues were uncovered that affect IRIDIUM’s ability to support FTS applications. The two most important were link availability and data latency. The link availability was calculated at 0.9661 percent, which is well below the RCC 319 requirement of 0.999 percent. Latency issues were caused by data buffering and delayed FTS commands for up to four seconds.

a. Link Availability. Communications links robustness is typically measured in terms of link availability. Availability assumes that a repair, with some Mean Time Between Failure (MTBF) Analysis, can be performed. Detailed availability information is not available from IRIDIUM or Boeing (operators of the network). The RAFS Risk Reduction testing estimated availability by measuring performance (downtime vs. mission time) over an extended time interval. The measured results showed performance for all aspects of the communications infrastructure. Results of the initial testing, based on more than 103 hours of test time randomly distributed over approximately five months, are shown in Table 1-2. Analysis of the collected data and discussions with Boeing, provided insight into the IRIDIUM disconnect mechanisms. Table 1-2 shows two availability numbers: source disconnect time and destination disconnect time. The difference is due to the observed disconnection process. First, the IRIDIUM L-Band Transceiver (LBT) in the RAFS airborne system (the destination) stops accepting data, and is effectively disconnected. Some time later the IRIDIUM Gateway receives an indication of a disconnect and passes this information to the RAFS ground station (the source). The net result of this process is that disconnect times based on the destination statistics are greater than the disconnect times based on the source statistics.

Note that each item in Table 1-2 was generated by processing each event on an event-by-event basis. Consequently, a small round-off error exists within the table (when converting hours, minutes, and seconds) which does not affect the computed results.

TABLE 1-2. LINK AVAILABILITY ANALYSIS FOR PUBLICE SWITCHED TELEPHONE NETWORK (PSTN) CONNECTION METHOD

Sum Total Time (Seconds)	373004.00
Sum Total Time (Minutes)	6216.73
Sum Total Time (Hours)	103.61
Sum Source Disconnect Time (Seconds)	4151.00
Sum Source Disconnect Time (Minutes)	69.18
Sum Source Disconnect Time (Hours)	1.15
Sum Destination Disconnect Time (Seconds)	12631.26
Sum Destination Disconnect Time (Minutes):	210.52
Sum Destination Disconnect Time (Hours):	3.51
Link Availability (source disconnect time):	0.9889
Link Availability (destination disconnect time):	0.9661

The previously described disconnection mechanism suggests the use of a protocol to reduce disconnect times by forcing the destination to disconnect after a set timeout. Given that a disconnect occurs because of an inter-satellite link hand-off condition (which allows rapid re-connection), application unique protocol software could reduce the disconnect time. This software, which uses periodic “heartbeat” messages to monitor the infrastructure health (availability), was recently tested. Based on a single 24 hour test period, a significant availability improvement was observed. The algorithm was added to the RAFS Basic Ground Station’s software. A patent has been submitted for the reconnection algorithm.

The team observed another disconnection phenomenon. These disconnects, although infrequent, lasted longer than 4 minutes, are probably (according to Boeing) due to failed spot beams on the satellite. During the previously described 24 hour test, one of these types of disconnects occurred. These disconnects may be mitigated by mission planning; i.e., predicting outages based on spacecraft health. This issue should be a future topic of discussion with IRIDIUM/Boeing. If the disconnects can be mitigated, the end-to-end availability could be further improved.

According to Boeing, the disconnections that allow rapid re-connection are probably occurring during the inter-satellite hand-off process (as one satellite leaves the field of view and transfers the user to another satellite). Boeing personnel feel that this is a fault condition due to software within the LBT. The next version of LBT software is expected to reduce the number of disconnects and will improve communications infrastructure availability. Also, an analog PSTN line is used to connect the RAFS Ground Station to the IRIDIUM Gateway. According to Boeing, the use of a network connection instead of a PSTN will significantly reduce the connection time.

b. Latency. Latency is the difference between the time a data packet is transmitted by the source unit (RAFS Ground Station) and when it is received by the destination unit (RAFS Airborne Unit). Latency consists of propagation time over the telephone network from the RAFS Ground Station to the IRIDIUM Gateway, IRIDIUM Gateway processing delay, IRIDIUM Gateway to satellite propagation delay, satellite processing delay, satellite to LBT delay, LBT processing time, and RAFS airborne system processing time.

A spreadsheet was built to analyze latency. The spreadsheet accepted data (manual entry) calculated for each area that added time to the propagation delay and generated an overall delay. The spreadsheet contained an “include” flag, which indicated whether a destination file would be included in the final computation. This was needed because some test runs used to determine link margin were conducted with high in-line attenuation (as much as 12 dB). The added attenuation significantly increased latency (by intent, to determine link margin). An analysis was performed for both conditions, since it provides insight into degraded link impact on overall performance.

A weighted average for the various percentile latencies was calculated, as shown below:

$$\text{Average \% latency} = \sum_{N=1}^{\#\text{ of files}} \frac{\#\text{ of samples in file N}}{\text{Total samples in all files}} \times (\text{\% latency for file N})$$

An analysis was performed for all RAFS configurations and found that buffering in the IRIDIUM Gateway and within the RAFS airborne unit caused intermittent delay patterns that reached 4 seconds at peak network operating times. Delay times versus probability are provided in Figure 1-2. This figure simply expresses the probability that a data packet will be delayed for a certain amount of time. For instance, there is a 96.7 percent chance that an FTS command (i.e., a data packet) will be delayed 4 seconds.

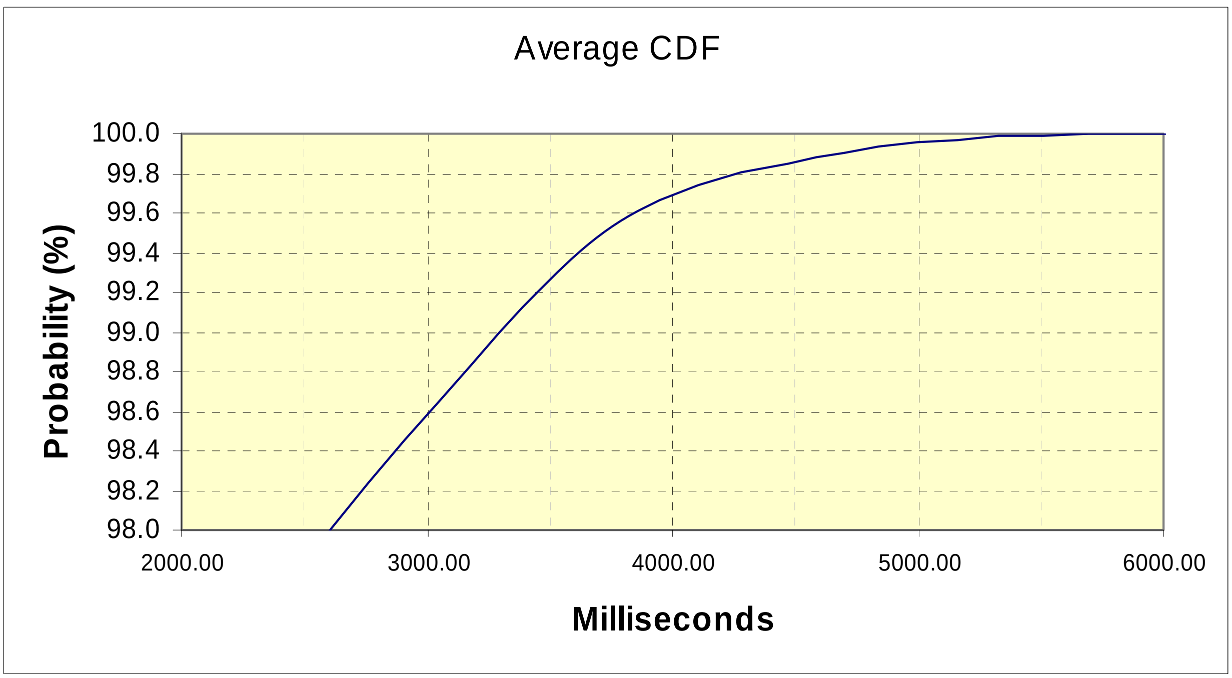

Figure 1-2. Delay versus Probablilty

The latency problem is caused by extensive data buffering due to the IRIDIUM Acquisition-No Acquisition (ACK-NAK) process, needed to guarantee data delivery (per Boeing, and verified by collected data). Voice calls (the primary purpose for IRIDIUM), which do not provide guaranteed delivery, have short drop-outs vs. high latency (example: recent F-16 test). According to IRIDIUM, it is possible to disable the guaranteed data delivery process for data calls. Then, only a "basic" latency (~600 ms) will occur (no higher latencies). This basic latency comes, however, at the expense of guaranteed data delivery and potential data errors. This may be acceptable because:

a. RAFS short command messages are protected with authentication & Triple Data Encryption Standard (3-DES) encryption, as well as a Cyclic Redundancy Check (CRC).
b. All valid commands from the RAFS ground station are positively acknowledged by the RAFS airborne system.
c. Multiple sequential commands can be sent until this acknowledgement is received to alleviate the potential missed messages.

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CHAPTER 2

SUMMARY

The RS-39 task looked at a number of FTS alternatives for UAVs flying over populated areas, outside restricted airspace, beyond line-of-sight, or that have demonstrated reliability making FTS undesirable or unnecessary but for which some positive control was still warranted. Over 60 terrestrial and space-based systems were analyzed. The terrestrial systems failed to meet the minimum requirements set forth by the RCC RSG. Space-based systems (e.g., satellites) presented the best options, but most were eliminated from consideration for many of the same reasons as the terrestrial systems. The alternative that met the highest number of the RS-39 task requirements was the IRIDIUM satellite network. A working prototype of the system was developed and demonstrated. Although considered successful, the prototype system uncovered issues that require further study and must be corrected before an operational implementation is possible. A full technology report is available at the AFFTC. You can reach the point of contact listed at the Preface in the front of this document.