A DATA LINK FOR COLLISION AVOIDANCE, PRECISION LANDING APPROACHES, AND COMMUNICATION

The following describes a Frequency Modulation digital Data radio Link (FMDL). When combined with the existing Global-Positioning-System (GPS), the data link would provide a precise and error free Collision Avoidance System (CAS). The same data link would provide the correction data for Differential-Global-Positioning-System (DGPS) precision approaches. It would also support textual messages such as Air Traffic Control (ATC) instructions.

A Collision Avoidance System based on the GPS is an obvious idea. Aircraft would broadcast their precise three-dimensional position and velocity to each other periodically. Such a system would be so accurate that it would eliminate the "cry-wolf" false alarms generated by the present TCAS system.

This system would also simplify the ATC task by allowing aircraft to truly "see and avoid" each other. The sole purpose of ATC is to prevent collisions. In this effort, the present, ground-based, human and machine system, assigns hard altitudes, speeds, and routes to provide separation. Aircraft can be assigned altitudes that produce icing, out of the way routes, or speeds that can be excessive in turbulence. Throughput is limited by the low information bandwidth of voice communication and the poor resolution of the one giga-Hertz radar. The present system is over-burdened and inherently error prone.

The difficult piece of a GPS based CAS, the twelve billion dollar GPS, is already implemented and working well. The satellites are up, and aircraft are navigating today with GPS receivers costing as little as six hundred dollars.

Definition of the necessary radio data link remains to be done. Various efforts are under way, but the proposals are complex and costly. Some treat the problem as a computer network with attention to protocol and arbitration to insure that transmissions do not interfere with each other. The problem is complicated because the time-distances between transmitters and receivers are dynamic. The network proposals involve large, ground-based, hardware/software systems that, historically, have missed objectives after years of expensive development.

THE ADVANTAGE OF FREQUENCY MODULATION

The proposed FMDL avoids coordination and arbitration all together, resulting in enormous simplification. Each aircraft transmits short data packets without regard to potential coincidence with other packets. All transmissions are in a single channel. Occasionally, packets will arrive at a receiver overlapping in time. By using Frequency Modulation, only the data from the further aircraft will be lost. The stronger data packet, from the closer aircraft, is received accurately. This is as it should be. <u>It is this important point that makes FM attractive.</u> The FAA's new Mode-S employs Amplitude Modulation (AM) and coincidences result in the loss of both packets. A distant aircraft can destroy data from a closer, threatening, aircraft.

12/29/97 Addendum to original paper:

NO ARBITRATION DOES NOT MEAN TOTAL ANARCHY

It was mentioned earlier, that packet transmissions occur roughly once per second with the period varied by a pseudo-random variable. Obviously, a transmission would not be started if currently receiving a valid packet. This means that a single emitter, say Air Traffic Control, could silence all other emitters by transmitting continuously for multiple packet times. Five packet times (1.125 milliseconds) would allow for 150 miles of propagation delay and assure that all aircraft in the area would receive ATC's important message without interference. Such a preemptive message might be a short text instruction to a single aircraft or it could be a one-second long, 100 K byte graphic of ground-based weather radar useful to all aircraft.

CAPTURE

The absence of interference from the weaker signal is by virtue of the phenomenon of CAPTURE. If two FM signals occupy the same channel, the stronger is received without interference from the weaker. It is CAPTURE that allows the Cellular Telephone System to support thousands of conversations on hundreds of channels. See Appendix-A for a heuristic explanation of CAPTURE.

THE PACKET

Assuming a data packet 225 bits long, at a 1 megabit rate, and transmitted once a second, the duty cycle would be one part in 4444. The transmission intervals would vary in a pseudo random way to avoid lock-step coincidence with other aircraft. The data would include the aircraft identification and type, three-dimensional position and velocity, a check-sum for error detection, and other items listed in Appendix-B.

STATISTICS

To examine the statistics of packet coincidence, imagine an aircraft called "A" at the center of circular area with a 50-mile radius. Assume that there are one thousand aircraft operating in this dense traffic area. Aircraft B transmits a packet when it is 5 miles from A. The probability that the packet received by A is damaged by coincidence is 0.0045. The probability that two successive packets would be damaged (two seconds without fresh data) would be twenty parts in one million. In the rare case that the B packet is damaged, remember that good data is received from an aircraft even closer than B.

Now imagine aircraft C at the edge of the area, 50 miles from the center. There are 998 aircraft closer to A than C is. The probability that a packet from C will not be received by A is 0.45. The average update period has degraded to almost two seconds. However, if C and A are closing at 500 knots, they are six minutes apart, and the update rate improves as they grow closer. Since there are 998 closer aircraft, aircraft A probably has other concerns anyway.

AIR TRAFFIC CONTROL

But now, suppose that A is an air traffic controller on the ground, routing arrivals to a major airport. He is interested in aircraft C even though it is 50 miles away. His average update rate on C would still be five times better than surveillance radar. Because the latitude and longitude data have resolution of four feet, the traffic controller's screen would be much more precise than his present radar system. He could filter his display to present only aircraft with a particular destination, a range of altitudes, types, speeds, etc. The aircraft identification and type fields would further reduce the controller's work load. Clearly, the FMDL is robust and has the capacity for the most ambitious traffic projections.

A message field would be part of the packet and would allow passing textual messages. If nothing more, an aircraft could put its destination airport in this field. Air Traffic Control could use the entire packet to send instructions and clearances to aircraft.

The smallest control tower could have a graphic display of traffic based on a $1500 personal computer with a packet receiver connected to a comm port. The computer could also write all packets transmitted in the Airport Traffic Area to a hard disk drive for an accurate and complete log of operations.

VELOCITY

It was mentioned previously that velocity is a part of the data packet. This seems redundant since velocity could be calculated at the receiver by differencing two position reports. Why use packet space for velocity? The typical GPS receiver determines vector velocity accurately and quickly by examining the reconstituted satellite carriers. It does not simply difference position data. Walking in different directions with a hand-held GPS receiver demonstrates this capability impressively. With this very accurate velocity, position can be predicted between transmissions. The blip on a controller's screen would move smoothly and continuously instead of in one second jerks. What is more important, the velocity data greatly improves the accuracy of collision prediction algorithms, reducing the likelihood of "cry wolf" false alarms. Even at a low level, false alarms can render a warning system useless or dangerous. The FAA's TCAS engineers are painfully aware of this.

ACCURACY

The position accuracy of the civil GPS is purposely degraded with a technique called "Selective Availability" (SA), which produces dynamic errors of a few hundred meters. This degraded position accuracy is still better than what can be attained by the radar based TCAS system.

The errors can be reduced to a few meters with Differential-GPS (DGPS). Satellite correction data from a reference GPS receiver at a known, fixed, location, are transmitted to those who need it. Such systems are already in place for precise marine navigation. There is also a proposed system that would transmit correction data derived from several ground reference stations via satellite up/down-links. The down-link would use the civil GPS channel and could be received by the on-board GPS receiver, saving hardware. Another thought: Perhaps SA could simply be turned off as it was during the Persian Gulf conflict.

The collision threat algorithm needs only relative, not absolute, position data. If all the aircraft in an area were transmitting positions with the same errors, their relative positions would have DGPS accuracy without the need for correction data. This would require that all aircraft calculate their position in the same way, using the same satellites, at the same time. Unfortunately, present day receivers calculate position with the manufacturer's notion of an optimum, which changes with satellite geometry and signal strength. Each manufacturer probably does it differently. The present SA degraded position accuracy is sufficient for CAS and the very precise velocity vector is not degraded by SA.

The GPS also provides precise absolute time. If all aircraft made their time differential measurements at the same absolute times, say once every whole integer second, the accuracy would be further enhanced.

INSTRUMENT APPROACHES

GPS precision instrument approaches will require DGPS accuracy. If the satellite correction system is not implemented in the short term, the FMDL could be used by placing a reference GPS receiver and packet transmitter at an airport. The hardware might be identical to an aircraft system with the addition of a weather tight box. It would transmit the GPS correction data, and perhaps, local real-time weather data. This would allow the definition of an infinite number of approaches to all nearby runways. In the cockpit, it would be reassuring to know that the steering data is derived using correction data taken at the destination airport and not at some point hundreds of miles away. There is something unnerving about subtracting two large numbers to arrive at small course and glide path deviations. Large atmospheric or ionospheric disturbances are another concern but may be insignificant. Taking correction data locally eliminates this concern.

ADDITIONAL APPLICATIONS

Taxiing to or from the gate at a complex airport can be the most difficult part of a flight. A moving map of the airport surface displaying ground traffic would prevent the tragic runway incursion accidents of past years. With DGPS, the accuracy would be a fraction of the width of a taxiway and could allow automating ground movements without buried wires.

Logging could be productive for locating downed aircraft. Search the hard disk drive for the aircraft ID. If found, the final packet transmissions would contain position and precise vector velocity pointing at the impact location. A 500-megabyte disk drive recording all packets for 100 aircraft would rollover in 60 hours. A 50-gigabyte tape drive would rollover in 250 days. The logging program could reject nine out of ten packets from aircraft moving at constant altitude and heading, greatly increasing the rollover times. A remote computer could be contacted over phone lines to conduct a data search.

Obstructions could be marked with the system. A unit, near an array of antenna towers, could pretend to be several units, one on the top of each tower.

Vessels could share the system without interfering with aircraft usage. Because of their lower speed, one tenth the packet rate and one tenth the transmitter power would warn of a potential collision with time to spare.

Public safety and transit vehicles could use the system for dispatch and rapid response to emergencies.

COST

For such a system to be practical, the airborne equipment must be affordable. To operate in protected airspace today, an aircraft is required to have an altitude reporting radar transponder. Similarly, this proposal would require a minimum system of a GPS receiver connected through a micro-controller to a packet transmitter. GPS receiver modules, smaller than a deck of cards, are already available from such notables as Motorola and Rockwell at around $300. The packet transmitter would produce only a few watts peak power and miliWatts of average power. If the channel were in the 500 to 1000 MHz range, the hardware could capitalize on high volume, low cost, integrated circuits intended for Cellular phones. The antenna would be a simple quarter wave vertical about the size of a transponder antenna. Installed system costs would be comparable to a low-end light plane transponder.

MODULARITY

The airborne equipment is neatly modular. Adding a user interface to a minimum system would provide GPS navigation capability. An added packet receiver would provide traffic warnings. Less cost-sensitive, large aircraft, would use a graphics screen displaying traffic on a moving map along with textual messages from ATC and audio voiced threat warnings.

CONCLUSION

There is nothing exotic or difficult about the FMDL. It uses available hardware and the software systems are small, stand-alone programs. It would provide superb "see and avoid" collision warnings that are independent of ground-based machine or human intervention, and free of "cry wolf" alarms characteristic of TCAS. The ATC surveillance performance far exceeds the present radar system, even with the proposed Mode-S patches. In fact, many believe that the additional burden of Mode-S and TCAS on 1090 MHz is bringing the radar system to it's knees in high density areas right now. They suggest that signal density at 1090 MHz, not aircraft density, is limiting throughput at major airports. The FMDL is independent of these existing ATC Systems and thus would not disrupt them during implementation.

Performance concerns aside, General Aviation is intimidated by the high cost of Mode-S and TCAS. The low cost GPS-FMDL solution would be beneficial to everyone, not just ATC. It provides not only ATC surveillance, but GPS navigation, CAS, and textual communication. Because of simplicity, the definition and implementation could take place quickly. The effort might be somewhat of a labor of love, in that engineers usually have to fly on airplanes. So do politicians. In a short time, the convenience and safety of flight would improve, and the cost of ATC would decrease.

Appendix-A
A Heuristic Explanation of Capture

Consider a digital Frequency Modulation signal that represents a binary zero with the frequency of 1000 MHz and a binary one with a frequency of 1001 MHz. Now consider the sum of two such signals. For simplicity, signal A is a steady stream of zeros and signal B is a steady stream of ones.

These signals can be represented as vectors in a complex plane coordinate system. If we imagine that the coordinate system is rotating clockwise at 1000 MHz, the A signal will appear stationary. We are interested in the sum A + B formed by placing the vectors tail to head. B will appear to rotate CCW at 1 MHz in the rotating coordinate system, forming the circular locus of the sum.

In the upper figure 1, B is the stronger signal, and the sum circle encloses the origin. The average rotation rate or frequency of the sum would be 1 MHz plus the 1000 MHz of the rotating coordinate system, exactly 1001 MHz, or a data stream of continuous ones.

In the lower figure 1, B is the weaker signal, and the sum does not make complete revolutions about the origin, but simply oscillates about the phase of A. Since there is no rotation the frequency is 0 + 1000 MHz or a stream of zeros.

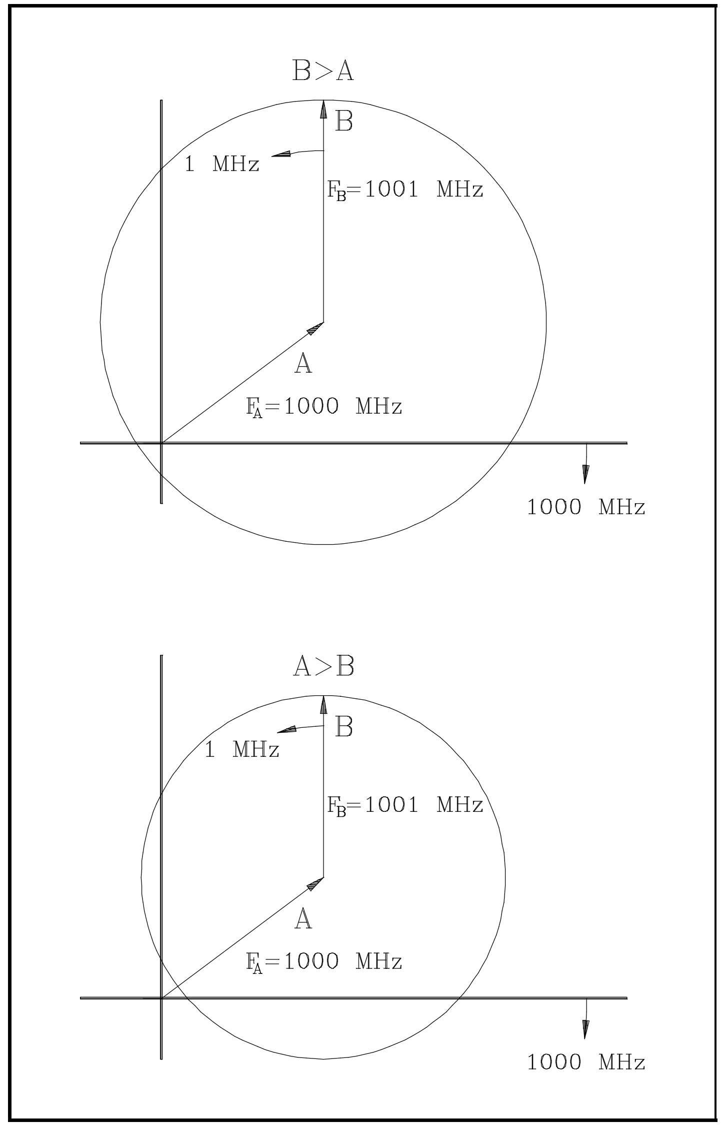


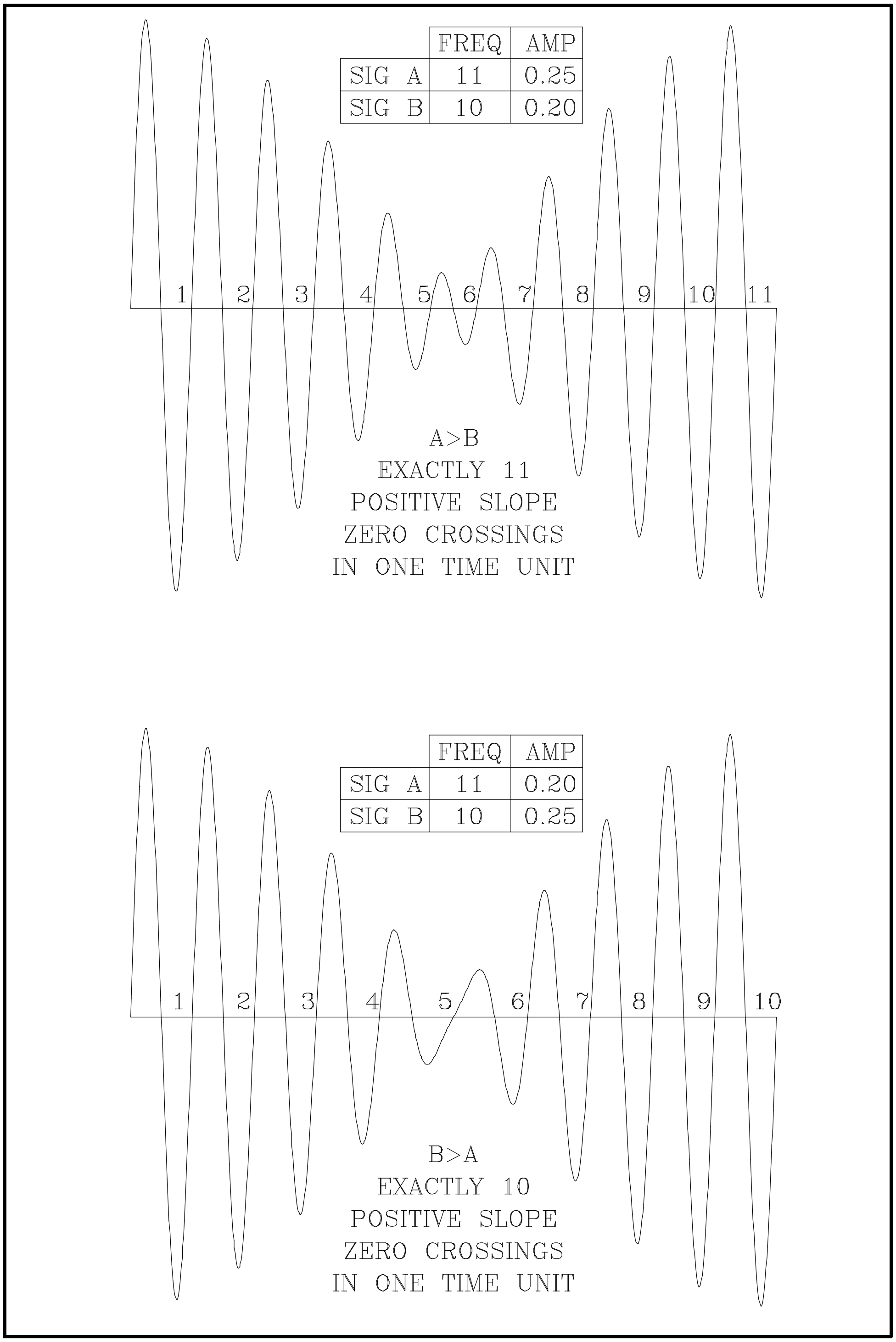
FIGURE 1

It appears that the stronger signal is received faithfully no matter how close the amplitudes are. In reality it does not work this well. As the ratio of the amplitudes approaches unity, the rate of change of the phase near the origin approaches infinity and the amplitude approaches zero. The limiter would require infinite gain and the FM discriminator would require infinite bandwidth.

The term "capture ratio" is used to characterize practical FM receivers. It is the ratio of the amplitudes of two signals at the point of a defined low level of degradation of the demodulated information associated with the stronger signal. A quality FM broadcast receiver might have a capture ratio spec of one decibel.

Appendix-A continued
A Time Domain View of Capture

THE SUM OF TWO SINUSOIDS OF UNEQUAL AMPLITUDE AND FREQUENCY



Appendix-B
Packet Construction, Transmission, and Reception

This hypothetical packet example use specifics for the sake of explanation and is not optimal. Position and velocity are separated into terms that a pilot would understand instead of more compact binary vectors or satellite time differentials. Again, for clarity, a simple check sum is used instead of CRC or Hamming code techniques that would likely be employed.

The frequency modulation employs only two frequencies which is sometimes called Frequency Shift Keying (FSK). Using more than two frequencies would reduce the required bandwidth with an attendant reduction in simplicity. Employing Quadrature Amplitude Modulation (QAM) would greatly reduce the bandwidth required but would sacrifice the Capture advantage. Unlike other communication systems, only one channel is required, thus, bandwidth compression is not a key objective.

The packet transmitter spends most of its time in an off state. To transmit a packet, it turns on at 1001 MHz, the frequency associated with a logical "one". It transmits at this frequency for nine microseconds, which represents nine start bits. Next, 1000 MHz is transmitted for one microsecond, representing one stop bit. Then, the data in the following table is transmitted with one stop bit after each byte so that nine consecutive "ones" can only occur at the start of a packet. After 225 microseconds, the process is completed and the transmitter power returns to zero. The process is repeated roughly once per second with the period varied with a pseudo-random variable. The data is organized in bytes to accommodate low cost eight bit micro-controllers.

DATA	BYTES	CHARACTERISTICS
TYPE	1	256 POSSIBLE EMITTER AND MESSAGE TYPES
IDENTIFICATION	3	16,777,216 ID NUMBERS
LATITUDE	3	4 FEET RESOLUTION, FULL RANGE
LONGITUDE	3	4 FEET RESOLUTION, FULL RANGE
ALTITUDE	2	2 FEET RESOLUTION, 130,000 FEET FULL SCALE
TRACK	2	0.005 DEGREE RESOLUTION
SPEED	2	0.031 KNOT RESOLUTION, 2000 KT FULL SCALE
RATE OF CLIMB	2	1 FPM RESOLUTION, +-32767 FPM FULL SCALE
TEXT MESSAGE	4	32 BIT MESSAGE FRAGMENT
CHECK SUM	2	16 BITS FOR BYTE WIDE CHECK SUM
	24	176 INFORMATION BITS
		9 PACKET START BITS
		24 DATA BYTE STOP BITS
		16 CHECK SUM BITS
		225 TOTAL BITS

At the receiver end, nine consecutive "ones" indicates the start of a packet and the micro-controller stores the next 24 bytes in memory.   If a stronger packet were to arrive before all 24 bytes were received, the detection of nine consecutive "ones" would reset the memory pointer to overwrite the previous packet with the new, stronger packet.

While storing the information bytes, the micro-controller performs an accumulation (addition) of each of the first 22 bytes. This sum is compared to the check-sum sent in the last two bytes. If not equal, the data is discarded by resetting memory pointer. If equal, a time stamp is appended to the data and the pointer is moved to the next available space in memory.

When the micro-controller is not busy storing packets, it is analyzing the stored packets for collision threats, and deleting superseded, aging, and uninteresting packets.

TRANSMITTER POWER REQUIRED:

Assumptions:

Receiver noise figure of 4 db.
Bandwidth of 6 MHz at 1 GHz.
Signal to noise ratio of 10 db at 50 nautical miles.
Simple quarter wave vertical antennae (1.5 db gain each).

Peak power required: 4.52 Watt.
Average power:
1.02 miliWatt

The transmitter power required varies as the square of channel frequency. A channel at 500 MHz would require only 1.13 Watts peak power.

The low peak power yields low cost. The low average power means low heat and, with back-up battery power, the packet transmitter could play the role the Emergency Locator Transmitter (ELT) plays now. The low duty-cycle transmitter design would preclude the possibility of "stuck mike" channel jamming.

Many years ago, the FCC allocated 46 UHF television channels in the 500 to 800 MHz range. Today, it may be practical to reassign one of these channels for the FMDL.

Please direct comments or questions to:

Rit Keiter
2655 N Fitch Mtn Rd
Healdsburg CA 95448

Phone: Airborne Electronics, Rit Keiter, 707 542 6053
Fax 707 542 1281, Email to RITK@METRO.NET