A GPS-BASED AUTONOMOUS ONBOARD DESTRUCT SYSTEM

Daniel F. Alves, Jr.
Alpha Instrumentation and Information Management
and
Edward L. Keith
Senior Launch Vehicle System Engineer, Microcosm Inc.

Abstract

This paper examines the issues involved in replacing the current Range safety infrastructure with an autonomous range safety system based on GPS (Global Positioning Satellite) integrated navigation system solutions. Range safety is required in the first place because current launch vehicle navigation systems cannot meet a level of trust needed to determine if the mission is really under control and on course. Existing launch vehicle navigation is generally based on attitude and acceleration sensing instrumentation that are subject to drift, initialization errors and failures. Thus, a launch vehicle can easily be under the control of a seemingly operating navigation system, yet be steering the launch vehicle along an incorrect and dangerous flight path. Inertial-based navigation systems are good, but they cannot be trusted. The function of Range safety is to assure that untrustworthy navigation is backed up with a trusted system that has positive knowledge of the launch vehicle location, and the intelligence to decide when and where a launch vehicle must be destroyed. Combining inertial navigation, GPS derived position information and knowledge-based computer control has the potential to provide trusted and autonomous Range safety functions. The issues of autonomous Range safety are addressed in this paper.

Key Words.

Autonomous Onboard Destruct System, Range safety, Global Positioning System, GPS, Trusted autonomous Range safety, Range instrumentation, launch operations.

Introduction

All launch vehicles are inherently dangerous whenever they contain fuel or oxidizer, or whenever explosive devices are installed, or whenever toxic chemicals or high-pressure gasses are on board. A fully loaded medium or heavy-lift launch vehicle has the chemical energy equivalent of a small nuclear warhead. Launch vehicles continue to be safety hazards after liftoff, because they have the potential to go out of control and cause massive loss of life and severe property damage. The rocket stages remain hazardous after burnout because they will either become orbital debris, or fall to earth, or both. The critical safety issues are (1) safety on the ground with inherently dangerous systems, (2) safety in flight, or Range safety, (3) post-mission safety, and (4) the environmental safety of our planet. The focus of this discussion is how to improve range safety, with lower mission costs as a highly desirable natural byproduct.

By Public Law, all rocket and missile flight operations conducted under the auspices of the United States Government on National Ranges must be controlled in such a way that these flight operations must present no greater risk to the public than that imposed by the overflight of conventional aircraft. In carrying out this safety responsibility, the National Ranges have developed a vast and costly infrastructure of tracking radars, high power command transmitter sites, telemetry receiving stations and ground processing and display systems. These facilities allow a human being to follow the course of flight, and to transmit commands to the vehicle to alter its course. This infrastructure makes up the bulk of the total Range infrastructure, with the launching facilities constituting a small remainder of the whole. While this Range safety infrastructure is shared among several launch facilities, it must be entirely present for every launch and must be kept in a state of readiness to guarantee reliable operation, even when no flight operations are contemplated. This large organizational structure generates high standby costs, even when not being used for relatively infrequent launch operations.

It should be possible to replace this extensive and expensive range safety infrastructure with an autonomous range safety system based on GPS (Global Positioning System) navigation. Such a system would not be totally on-board because an integral part of the system would be the constellation of 24 NAVSTAR satellites, and the associated ground element comprising GPS. While this system is an extensive and expensive system, it is not strictly dedicated to the support of range safety for rocket and missile launch flights. This means that the cost to operate and maintain the system need not be borne mainly by the Range user, the launch vehicle operator. The extensive and myriad uses to which GPS is being put to positively guarantees that the cost to use it is all but free.

Current Method of Operation

The Range infrastructure necessary to support Range safety, as practiced today, is, as stated earlier, extensive and expensive, see Figure 1. This infrastructure typically consists of C-band tracking radars, positioned at the launch head as well as down-range. This is to guarantee that the vehicle will always present a strong target for tracking. This is necessary, as the present method of doing business requires that the location and velocity of the vehicle be known by Range's safety personnel on the ground at all times. This reliable tracking function is not required throughout the vehicle's total time of flight, but only during powered flight. This system is primarily used for Range safety, although the data generated may be useful to the range user for diagnostic purposes.

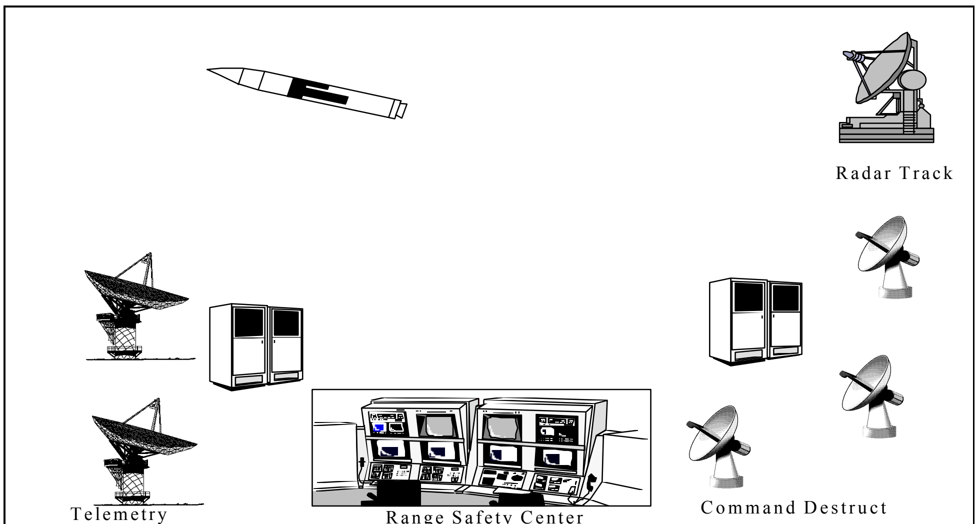

Figure 1 Current Method

Also required are high powered UHF transmitters and attendant transmitting antennas, to effect control. These transmitters are typically 50 Kw in output power, boosted by antenna gain to produce an extremely strong signal input to the vehicle's command receiving antenna system. The reason for this is that the command receivers are expected to be "captured" by these transmitters throughout powered flight, making use of a characteristic of FM signals that receivers will only respond to the strongest of competing input signals. It is only this feature which is relied upon by existing range safety systems to prevent unauthorized commands being received by the vehicle or to prevent a “takeover” by an unauthorized agency.

There are typically two antennas for each command transmitter site, an omnidirectional, for use during early flight, when the vehicle is relatively close and a tracking, directional antenna, for greater distances, later in flight. This is to insure a high signal level at the vehicle’s receiving antennas throughout powered flight, for security, as discussed above. The directional antennas receive their pointing data from the C-band tracking radars.

Because of reliability concerns, there are typically two independent transmitter chains at each site, to insure coverage in case one transmitter fails during the mission. Also, to insure adequate signal deposition regardless of range or attitude, there are typically command transmitter sites at downrange and uprange locations. Not only is distance the driver but also aspect, or “look” angle, as it is desirable to not attempt to transmit commands to a vehicle flying directly away as the signal is subject to the attenuating effects of the hot rocket engine exhaust plume. The command transmitter system is solely and totally dedicated to the Range safety mission and generally provides no direct benefit to the Range user.

The Range also must have in place a Telemetry receiving system, consisting of high-gain antennas (typically tracking, directional antennas) and sensitive receivers, decommutators and data processors to generate health and status, actual discrete event timing and inertial guidance (TMIG) information. This data, converted to engineering units, is used by Range safety to assess, in real time, the reliability of the vehicle. Again, these sites are typically located at the launch head and downrange, to insure adequate received signal strength. “Look “ angles, as discussed above, are a consideration. The antennas are slaved to the tracking radars for pointing.

Additionally, Range safety requires a processing system to provide and display data in real-time during flight. This includes all the tracking data from the C-band radars to provide, not only pointing data to the command transmitter and the telemetry receiver antennas, but also to drive the display the Range Safety Officer (RSO) uses to follow the flight and make his decisions to allow or terminate the mission. Real-time processing of tracking data and telemetry are not generally of great use to the Range user, with the exception, of course of pointing data for the telemetry antennas. Post processed data is generally more complete and more accurate.

In order to support the Range safety operation, the launch vehicle must have some sort of command receiver (including appropriate vehicle destruct mechanisms), a Time Space Position Information (TSPI) device (almost always a C-Band radar beacon) and a telemetry system (for health and status information), plus appropriate dedicated power systems on board. This Range-required payload can take up to several hundred pounds of weight and several cubic feet of space in the vehicle, Since it is mostly concentrated in the upper stage of the vehicle, it subtracts, pound for pound, from payload. This equipment is used by the Range's flight safety personnel to track the vehicle throughout launch and flight, terminating any flight before it poses a hazard to lives and property.

The requirement to provide a level of hazard no greater than that posed by the overflight of conventional aircraft, referred to as the protection of lives and property, is balanced by the need for a flight to accomplish its stated goals, be they the successful insertion of a satellite into a useful orbit or the accurate impact of an ICBM reentry vehicle, referred to as mission success. While Range safety cannot be driven by mission success criteria, it ignores them at its own peril. This leads directly to the extensive ground infrastructure discussed above, as the existence of a large, reliable, redundant system, coupled to redundant systems aboard the vehicle, drastically lowers the type II, or Beta, risk of terminating the flight of a good vehicle due to receiving false data as to its health. Also, having such an extensive, overlapping architecture, albeit an expensive one, lowers the type I, or Alpha, risk of failing to terminate the flight of an errant vehicle, either by falsely believing that the vehicle is not errant, or by being unable to have the vehicle respond to a termination command signal.

Putting Range Safety Requirements in Perspective.

The birth of Range Safety can be traced back to the flight of a V-2 rocket from White Sands, New Mexico on May 29, 1947. The Rocket flew south instead of the planned trajectory north toward the planned impact area. The accident became an international incident because the missile impacted south of the border onto a graveyard in Juarez Mexico. Fortunately no one was injured because the inhabitants were already dead. The so-called Juarez Incident was a wake up call that spawned Range Safety. The problem was the navigation of rocket vehicles could not be trusted. This factor, along with the inherent low reliability of early rocket systems, made these launch vehicles particularly dangerous.

After the Juarez Incident accident, the US Army installed Radar systems and automatic plotting boards to track all rocket launches, and to predict the point of impact. Safety had to diverge from the method used in aircraft operations because the rocket navigation could not be trusted, and because there was no intelligence in the rocket. The gyro-based guidance package in rocket vehicles was subject or drift, errors in initial alignment and unexpected failure. The vehicle relied on the gyro-based guidance, but the system could not be trusted to give true position. Other defects in launch vehicles caused a large number of rockets to divert from the coarse set by the guidance system, but the launch vehicles of almost fifty years ago had no decision-making capability that would allow management of a safety problem. Rockets were inherently dangerous, their navigation system could not be trusted and they had no autonomous intelligence. Alternatives that are available today were unheard of back then. There were no desk-top computers, solid state electronics or precision navigation systems in the era of vacuum tube electronics. Therefore, all the Range Safety functions had to evolve on the ground, where the weight of these heavy Radar and computational devices was not a limiting factor.

The skies over the United States are filled with commercial, military and general aviation aircraft that are filled with flammable fuels. These aircraft concentrate the most dangerous activities, takeoff and landings, over crowded metropolitan areas. These aircraft, especially jumbo jets and military aircraft, have destructive potential characteristics similar to launch vehicles. These aircraft exceed the flight rate of rockets by many orders of magnitude. These aircraft always had human intelligence in the loop. Therefore, aircraft had no system of tracking radar dedicated to destroying them, no explosive package, no telemetry and no dedicated up-link.

Launch vehicle and aircraft safety equipment followed two completely different philosophies of safety. The reason was driven by lack of compact intelligence and lack of trusted navigation for launch vehicles, back when the evolutionary paths of aircraft and rocket vehicle safety diverged almost fifty years ago. The question at bar is   can the paths converge again, now that compact GPS receivers and computers can put trust navigation and knowledge-based decision power into launch vehicle systems? Can black boxes replace telemetry, can GPS and computer systems replace pilot intelligence, and can airborne autonomy replace the manpower-intensive ground-based hardware on launch vehicle operations?

Current GN&C

In any case, unmanned vehicle navigation and control systems are not adequately reliable to meet the safety criterion stated, above, with the same low level of Alpha and Beta risk evidenced today. While it is possible to propose a guidance and control system which would be as reliable as the present extensive off- board system, the weight and complexity required would be prohibitively expensive and heavy. Basically, any onboard inertial system, that is, based upon attitude and acceleration sensing instrumentation, is subject to drift, initialization errors and failures. To overcome these deficiencies would require a high degree of redundancy to reduce type Alpha risk, an errant vehicle incorrectly sensing nominal flight, to an acceptably low level. Reducing type Beta risk to insure mission success, requires the same extensive redundancy

More than TSPI data is utilized in determining whether a vehicle is to be allowed to continue flight. Health and status indicators, such as chamber pressures and accomplishment of discrete events, such as staging, is telemetered to the off-board range safety system, along with inertial guidance data (TMIG). The display provided to the ground-based human decision-maker includes not only the information obtained from the tracking radars (TSPI), but TMIG and health and status information, as well.

Man-In-The-Loop

Another problem with the existing system is the fact that there IS a man in the loop. The decision to terminate flight, actually a decision to render a thrusting vehicle ballistic and thus accurately predict its impact point, is decided by a highly trained human being. Granted, the training is extensive because the requirement for high proficiency leads to an extensive training and certification program, with periodic recertification and constant practice on simulations. But the fact remains that having a "man in the loop" creates a built-in delay which translates into a more conservative set of standards than might otherwise be in order to provide time for a human to react. Typically, the Mission Flight Control Officer (MFCO) or Flight Safety Officer (FSO) will observe the progress of the mission on a display which portrays not the present position of the vehicle but rather where the vehicle would impact if it lost thrust and went ballistic at that point in time. The decision to terminate flight is made when that trace shows that the ballistic impact point is moving to an area which it is desired to protect from such an eventuality. The processing which generates this display adds in a time factor to account for human decision and reaction time. the end result is a set of flight criteria with respect to trajectory which is more stringent than it need be. If an expert system were developed and used for this decision-making, Type Beta risk would be further reduced, increasing the margin of mission success.

A very real advantage of an on-board system is the elimination of the man in the loop and the decision delay time built into the existing, ground-based system to allow time for a decision. By not requiring this delay, the safe flight rules loaded in the onboard flight safety computer prior to launch need not have that pad included, allowing the vehicle to potentially fly a more nonnominal borderline trajectory than a manned safety system would allow, thus increasing the probability of mission success.

Cost Reductions

One key to safe cost reduction, concurrent with increased in-flight safety, is the concept of trusted autonomous range safety. Trusted autonomous range safety is a system of instrumenting a launch vehicle to know with certainty where it is, what is it's condition and when it must be disabled for safety reasons. The certainty of navigation can be solved with Global Positioning Satellite (GPS) technology. GPS satellite receivers are the devices that resolve the exact position and velocity of the receiver by solving timing differences from signals sent by Navstar satellites. GPS solutions can be trusted, unlike the inertial navigation systems that have been aboard launch vehicles of the past. Compact, low-cost solid state computers, and GPS-based navigation systems, have the potential of replacing the multiple radar sites and command distruct transmitter sites required for ground-based Range safety. The radar sites and technicians required for range safety must be employed at all times, no matter how infrequent launch operations are flown. One small electronic black box has the potential to render many expensive radar sites, and a small army of technicians, obsolete and unnecessary. The same technology has the potential to make any remote location into a practical launch range, see Figure 2.

An on-board system could use GPS to provide TSPI data to an on-board computer wherein would reside an independent copy of the trajectory and guidance information used by the vehicle's guidance computer. Since GPS can provide a solution as to the vehicle's location at any point in time, it becomes a simple matter to compare the GPS position solution to the guidance computer's solution and terminate powered flight if there is a discrepancy between the two computer outputs or if the two computer outputs agree on a nonnominal trajectory.

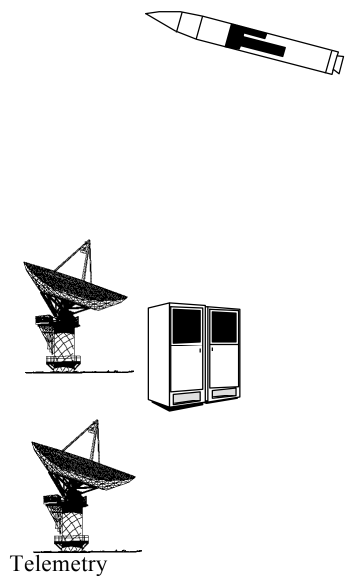

Figure 2 With AODS

However, this assumes a perfect world and there is no such thing as a perfect world. There are uncertainties and time delays in GPS and GPS reliabilities to consider. Also, there is the very real possibility that the on-board receiver would break lock during high G maneuvers, thus causing a potentially disastrous discontinuity. The solution to this problem is to add an inertial platform, preferably a small strapdown unit, to the system. This inertial platform would be initialized and periodically updated by the GPS receiver, thus smoothing the TSPI data input to the onboard Range safety computer.

The onboard Range safety computer must consider more than just the comparison of the trajectory of the rocket, according to the rocket's inertial guidance system, with the TSPI being provided by the inertial-smoothed GPS data. It must also take into consideration such health and status information as engine chamber pressures, time/pressure profiles, inboard temperatures and such discretes as staging times.

Preflight planning and operations would then consist not only of loading the "targeting" parameters into the guidance computer, but also loading similar information into the on-board Range safety computer, along with additional data, such as mission discretes and health and status data. The Range safety computer would then follow the course of the flight, using the TSPI data provided by inertial-smoothed

GPS and correlating the timing of events during flight and monitoring the continued health of the vehicle. The Range safety computer would also have as part of its load, the precalculated impact limit lines or debris ellipses appropriate to the mission's flyout profile.

Given this information, the on-board Range safety computer would have all the information used by a ground-based human to make fly or terminate decisions. While it might be said that the reasoning potential of a human being is necessary to properly assess the risk and, most especially, the timing of the decision, it can be seen that a significant increase in Beta risk to keep Alpha risk at existing levels would still result in keeping overall costs lower than existing levels, given the reduction in ground systems. It is by no means certain that a large increase in Beta risk would be necessary, however.

Costs cannot only be reduced as a result of the elimination of the ground system but also by the reduction in size and weight in today's required onboard instrumentation suite, which is required to interface with the ground system. Due to the multiplicity of radio frequencies used and the need for redundancy and dedicated power supplies, the onboard instrumentation is actually more extensive, heavier and bulkier than an autonomous onboard destruct system would be. It would seem to fly in the face of reason that a system which is largely reusable, as the present system is, would be more expensive than a system which accomplishes the same task but is replaced after every flight. One need only contemplate the Space Shuttle to realize that reusability need not translate into lower costs. Also, the recent advances in low cost, powerful computers and the proliferation of GPS receiver technology provides a strong indication that costs for an autonomous onboard destruct system would not only not be excessive but quite reasonable, all the while meeting the stated risk criteria.

The present extensive ground-based offboard instrumentation suite which makes up the Range poses limits because of its size and complexity. Such an extensive infrastructure is prohibitively expensive to duplicate, thus limiting the proliferation of vehicle launch sites to those places where this infrastructure exists or to where there is sufficient capital to build not only the relatively inexpensive launch pad but this instrumentation suite, as well. This cost barrier has worked against the fledgling commercial space industry. Efforts to start truly commercial, or at least, non-Federal, launch heads in Alaska, Hawaii and Canada, have all had to wrestle with the formidable investment required to provide even a "bare-bones" instrumentation suite. Actually, "bare-bones" is not really any less extensive than the existing suites at the existing ranges, the need to lower the risk through redundancy drives a proliferation of instrumentation.

Eliminating the extensive ground instrumentation suite would allow vehicle flight operations to take place anywhere a relatively simple and primitive launch pad could be built and an acceptably safe flyout corridor could be flown. This could lower the cost of a pound to orbit by a significant amount. It can be shown that the massive investment embodied in Range safety-required instrumentation contributes a significant amount to the overall cost of a pound to orbit, which is the best measure of the cost of access to space.

Resistance to Change

Why aren't such systems and procedures used today? Because of the all too human penchant against change. There is widespread belief among the missile and space launch community that the way things are done today represents the best that can be accomplished and that only minor increases in effort or technology are necessary to maintain the safety record the Ranges have earned over the last few decades.

There are really two reasons for this. The first is the fear of change. The second is a mindset stemming from the earliest days of launch activity that safety of operations and mission success are, literally, priceless, and that any attempt to cut costs cannot be in the best interests of safe operation. This mindset is a product of the Cold War and the fact that, until quite recently, costs were not a concern. It was a Government monopoly and costs were simply to be borne by the taxpayer. More recently, with the large scale entry of commercial entities into space, the issue of costs has been brought up. Can an acceptable level of safety be bought at lower cost?

Up until now, the answer on the part of the Ranges, as launch heads, has been "no". The Ranges are Government entities, after all. Even the so-called Commercial Ranges or launch heads must play by Government rules, much as commercial aircraft operations and equipment must conform to Federal Aviation Administration (FAA) rules. The FAA, however, is also charged with the responsibility to foster aviation, as well as regulate it. There is no such corresponding charge on the part of any Government entity with regards to space.

Specific objections to an autonomous on-board flight termination system all center upon the man-machine interface and the need for a human being to be in the decision loop. It has been stated by personnel at the Ranges, that they do not believe that an expert system could be built which would be able gather, sense and react to all anomalous conditions in real time, and be light enough, compact enough and, most importantly, cheap enough, to seriously compete with the existing system. It must be pointed out that such a system would have the exact same vehicle information available to it as would the ground-based human and that sensing all anomalous conditions could be thought of as sensing all non-nominal conditions, a much easier task.

Another reason mentioned is cost. the cost to develop such a system would be prohibitively expensive. This seems to be reasonable when one considers that the Range infrastructure can be considered as sunk cost, already paid for. This does ignore the considerable costs incurred in maintaining and operating this infrastructure. These costs are not usually mentioned. Also, the development costs to retrofit existing vehicles is mentioned. Again, existing designs will probably not be around forever, although it may seem that way, and a new generation of vehicles could just as easily be adapted to autonomous on-board destruct as the existing system.

Conclusions

There is a tacit understanding and belief that low cost space transportation will naturally be less reliable, and less safe, than the current high-cost systems. After all, so the conventional wisdom assumes, the coin traded away for lower cost is less safety and lower reliability. Certainly it seems logical to assume that cutting the corners toward low costs will tend to sacrifice the care that maintains the current reliability record and safety standards. There is an opposite theory that states that the complexity of modern space transportation has driven up cost at the same time it has driven down reliability. Does the current space transportation infrastructure have severe safety hazards built-in, which increases the costs of operations at the same time? Can space transportation costs be reduced at the same time that safety is enhanced and reliability is improved? Surprisingly, the answer is yes!

Acknowledgment

Some sections of this paper are extracted from the pending book Space Transportation Economics, by Edward Keith and John London, John London is not listed as an author, yet his contribution toward this paper is significant.

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