The Space Congress® Proceedings | 1981 (18th) The Year of the Shuttle

Apr 1st, 8:00 AM

Experiences In Delta Mission Planning

Jyri Kork
Delta Mission Analysis Manager

EXPERIENCES IN DELTA MISSION PLANNING

Mr. Jyri Kork
Delta Mission Analysis Manager
Goddard Space Flight Center, NASA

ABSTRACT

In 1959 NASA decided to develop Delta as an interim launch vehicle for medium payloads until more sophisticated vehicles reached operational status. In the twenty years that have followed, Delta has matured into a versatile all-purpose launch vehicle, being utilized by various US government agencies, domestic industry, and a number of foreign governments, as well.

Delta's 153 launches have included low circular orbits, sun-synchronous, earth-synchronous, polar, lunar, and interplanetary missions. Delta's 'firsts' include the first international satellite, the first synchronous transfer orbit, the first polar launch from ETR, and the first lunar orbiter without a midcourse velocity correction.

Typical Delta mission analysis methods and results are reviewed: feasibility studies, trajectory shaping, payload, orbit and launch window optimizations, range safety studies, orbit injection error analyses, radar tracking coverage, and vehicle separation dynamics. A number of more picturesque cases of the above missions analyses are highlighted among the past 153 missions, as well as among the approximately 40 future missions presently scheduled for the Delta launch vehicle.

1) INTRODUCTION

In the beginning the Delta launch vehicle was modest and unassuming. The first launch attempt on Friday the 13th, May 1960 ended like the first launch of Vanguard: an unqualified failure. There was but one basic difference: Delta -- using a design based on the Vanguard second stage -- was able to solve its initial problems in only three months and to score 22 successive successes in the next 3 1/2 years, establishing a new reliability record for the early dawn of the Space Age. The pattern of surmounting difficulties and mastering hardships became somewhat of a Delta trademark, reflecting in the news media headlines such as the "Space Transportation Workhorse" and "The Indomitable Delta."

The philosophy of the Delta launch vehicle was unorthodox in its inherent simplicity: to utilize the latest up-to-date technology and flight proven hardware, to minimize the necessity of developing totally new flight components, while aiming for optimum performance, reliability, and cost effectiveness. Especially the stress on the cost effectiveness accounted for the spectacular popularity of the early Delta launch vehicles among the 'poor people of outer space' -- non-government missions, the reimbursable launches. In this respect -- without any false modesty -- Delta has probably been one of the best United States good will ambassadors in numerous widely separated areas of our common world.

Another basic Delta philosophy was to 'please the customer'. It involved many extra weekends of studies in the areas not spelled out in the formal contract: alternate launch windows, orbit optimizations over and beyond the call of duty, celestial mechanics lectures to foreign scientists just starting out on their road to the stars.

But above all the Delta launch vehicle placed a premium on versatility. Missions to be considered covered the whole spectrum of the space studies. Orbits ranged from the low circular ETR to the high circular WTR launches, geosynchronous transfer coast orbits, highly elliptic probes, to lunar, and even interplanetary missions.

Delta's 153 launches and 40 presently scheduled future missions will be discussed in the following technical review paper.

2) LAUNCH HISTORY

A direct outcome of the agreement of the United States in 1955 to participate in the International Geophysical Year (IGY) was the development of the Vanguard three-stage vehicle. In 1959 NASA decided to develop Delta as an interim launch vehicle for medium-class payloads until more sophisticated vehicles (such as Scout and Agena, then under development) reached operational status. The Vanguard second stage and the Vanguard third stage X-248 were adapted to the Thor booster to become the original and the first Delta configuration.

The Douglas Aircraft Company (presently McDonnell Douglas Astronautics Company - MDAC) was and still is the prime contractor for the Delta launch vehicle program. In the past 21 years this has been one of the most fruitful government/private industry cooperations. A considerable number of the members of the original Delta team are still operational at both outfits.

The Delta development program involved 12 vehicles of the DM-19 configuration, 11 of which were successful.

In 1962, characteristically, the Delta first stage was uprated (utilizing an Air Force Thor DM-21 first stage) and named Delta A. After changes in the vehicle control system and a fairly extensive ground-qualification program, Delta 13 and 14 were successfully launched in October 1962. Only two Delta A configurations were ever launched. The handwriting of the Delta was on the wall. A long history of the state-of-the-art performance improvements had just begun.

Delta B was improved by lengthening the second stage propellant tanks by three feet and changing the oxidizer from white inhibited fuming nitric acid (WIFNA) to inhibited red fuming nitric acid (IRFNA). It added roughly 100 lbs. to a 200 n. mi. circular orbit payload capability. In today's numbers it may look like a bag of peanuts, but let us remember that Vanguard I (still in orbit) was a whole total of 3.25 lbs.

Having weathered successfully the improvements of its first and second stages, it was only logical that the Delta management, in its orderly one-two-three punch sequence, next incorporated a new third stage solid propellant rocket X-258, developed for Scout. Quite properly, it was called Delta C. Both configurations were popular at their time: 9 Delta B-s and 12 Delta C-s were launched.

The trend of Delta performance improvements developed into a genuine trademark. An exasperated aerospace engineer (not totally sympathetic to Delta) once explained that launch vehicle statistics can only be calculated if configurations remain identical, which "is true for all of the vehicles but Delta, for which some wag has remarked that 'no two Delta flights have used identical configurations'."

Aerospace engineers have been known to occasionally exaggerate. Actually, there have been many Delta launches using the same configuration. Of the sum total of 32 Delta flight configurations (ref. 2, 3, 4) two were used definitely more than once: Delta E was flown on 22 missions and Delta 2914 on 30 missions. On the other hand, among the 32 development steps, four were used only once (Delta J, 1900, 1410, and 1913), while two became true space age collectors' items. Delta M6 and Delta 2314 were possible configurations that were never flown. Both, of course, were designed at the time when Delta came with three sets of interchangeable configurations -- 3, 6, and 9 solids. The spacecraft managers, as experience clearly shows, are in these cases apt to "get there fastest with the mostest" and pick the highest available payload...

No history is complete without the "firsts" that the newspapers used to list in their "scorebox" when outerspace was young.

The honor roll of these early satellite "firsts" for the Delta vehicle includes:

1) First passive communications sattelite (ECHO I)
2) First international satellite (ARIEL)
3) First privately owned satellite (TELSTAR)
4) First geosynchronous satellite (SYNCOM I)
5) First equatorial geosynchronous satellite (SYNCOM III)
6) First polar orbiter from ETR (TIROS I)
7) First commercial comsat (EARLY BIRD)
8) First operational weather satellite (ESSA I)
9) First lunar orbiter without midcourse velocity correction (AIMP-E)

But more than the "firsts", three points evolve from the past Delta history:

1) The cumulative launch success ratios have remained in the 92% to 95% region

2) The probability of on-time liftoff has remained unbelievably high:
   70% for a one second window
   90% for a five minute window

3) Reimbursable missions have become a mainstay of the Delta launch schedule.

3) MISSION PLANNING

For the purposes of this paper the mission hardware coordination schedules are not discussed and only mission analysis documentation is reviewed.

Spacecraft Restraints Manual. Whether a mission falls into the class of the Delta vehicle capabilities, can be approximately estimated from parametric performance curves maintained by Delta mission analysis engineers and published in the Delta Spacecraft Restraints Manuals (such as ref. 5). Delta Restraints Manuals include a considerable amount of data besides performance capabilities, such as spacecraft design restraints, safety considerations, hardware integration schedules and field operations reviews. Such manuals are freely distributed among prospective customers and spacecraft agencies already committed to a Delta launch.

Feasibility Study. For a totally new type of mission or a new vehicle configuration, a feasibility study must be conducted 2-3 years before the launch date. The feasibility study utilizes the best estimate of the physical model of the Delta launch vehicle, including possible future improvements. In incorporates a complete trajectory profile for sun-angle, radar tracking, and heat transfer studies, fixing the payload estimates within 50-100 lbs.

Reference Trajectory. Historically, the next step for a new type of a mission was a reference trajectory (roughly one year before the launch). It involved a parametric study required to define optimum performance capabilities for a particular set of mission requirements, such as apogee and perigee altitudes, orbit inclination, argument of perigee, nodal drift rate, etc. As all trajectories must satisfy numerous vehicle constraints, the generation of a reference trajectory used to take 128 trajectory simulations and 10 IBM machine hours, back in 1962. (ref. 1). Today, using computerized trajectory shaping models and the combined Delta experience of the past 21 years, such a reference trajectory can be obtained in just a couple of machine runs. Even better, as the Delta experience includes almost all possible mission profiles, the new customer, at this stage, will usually receive the already flown trajectory printout of a similar previous Delta mission.

Preliminary Mission Analysis (PMA). Today the first step of the mission planning that is 'tailor-made' for a particular spacecraft is the Preliminary Mission Analysis, published usually 8 months before the launch. PMA uses all mission requirements and S/C characteristics (weight, moments of inertia, etc.) in order to generate a trajectory sequence and profile. At this time the payload capability is fixed within a few pounds. PMA also includes range safety and vehicle dispersion analyses. Tables, probability distribution curves, and covariance matrices present predicted dispersions of all spacecraft injection conditions and classical orbital elements. A complete and detailed trajectory printout is included in the PMA.

Detailed Test Objectives (DTO). Approximately 5 months before the launch a DTO presents the total description of all flight objectives, the nominal trajectory printout, a sequence of events, a detailed weight breakdown, guidance times and rates, spacecraft and vehicle radar tracking data, physical flight conditions, and other pertinent information. DTO is used by MDAC to develop guidance targeting constants.

Range Safety (R/S) Studies. In the early days of Delta, roughly 2200 man-hours and over 700 IBM runs were needed for the R/S studies of a typical mission. As impacting an empty stage on Africa or Cuba is considered totally taboo, severe limitations on the payload capabilities can occur. For example, several hundreds of trajectories were run for the P-14 mission, before it was decided to change P-14 from a lunar to a highly elliptical mission, in order to move the second stage impact point off the African coast.

Guided Nominal Trajectory. As the weights of all the components of the spacecraft and the particular launch vehicle become finalized, updated, and weighed in, roughly 4-6 weeks before the liftoff, a guided nominal trajectory is generated. It basically verifies that the Delta Inertial Guidance System (DIGS) targeting constants actually result in all required mission specifications. The first stage portion of the flight is based on a five-degrees-of-freedom (5D) trajectory simulation, incorporating the effects of vehicle rotational dynamics and control system responses during the high aerodynamic loading portion of flight. The remainder of the trajectory is based on a three-degrees-of-freedom (3D) trajectory simulation. Engine deflections, guidance steering histories, and in certain cases even seasonal wind altitude profiles are incorporated and analyzed in the guided nominal.

Mission Specific Studies. Theoretical analyses specific to any particular spacecraft include in all cases a spring separation and miss distance analysis. If desired by the S/C project, other studies such as parametric orbit optimizations, launch window, sun-angle, shadow, and orbital lifetime histories are calculated. Delta mission analyses have included Pioneer spacecraft coning, preliminary Shuttle orbital maneuvers, Spacelab lifetime, ECHO balloon inflation, and other sometimes exotic studies.

Various new computer programs have been developed by the Delta Project Office and MDAC to solve specific mission related problems. For example, a program calculating the stability of lunar satellites, an earth atmospheric drag model accounting for both the diurnal and 11-year cyclic solar flux variations, a 6-degree-of-freedom spinning body motion analysis, interstellar targeting programs, etc. etc. Alone in the Delta Project Office computer library there are presently more than 200 computer programs for various areas of mission analysis.

4) TRAJECTORY SHAPING

The heart of successful mission analysis is in the trajectory shaping. This is the territory where the clean dreams of a rocketman meet the muddy, tangled swamp of reality. The main areas involved in this complicated problem are the vehicle and spacecraft constraints, the optimality of the trajectory shaping methods, and maximizing the payload capabilities.

Vehicle and Spacecraft Constraints. Obviously a trajectory should not be flown, if it presents any dangers to the structural integrity of either the vehicle or the spacecraft. Furthermore, it is a range safety requirement that no part of the vehicle (solids, first stage, fairing nose cone, etc.) can impact a land area. From the viewpoint of the vehicle structure the product of total angle of attack and dynamic pressure must be minimized during the time spent in the region of maximum dynamic pressure. The altitude-velocity profile must be selected so that a 400 F internal fairing wall temperature limit will not be exceeded during the atmospheric flight and the heat flux to the spacecraft at the fairing drop time does not exceed the solar heat input. Considering also the vehicle attitude rate limitations at all solid drop and stage separation times, it is easy to visualize that the mathematical trajectory shaping becomes a complicated balancing act, accessible only to the most sophisticated electronic computer programs. A good trajectory analysis program (such as the MDAC old AB60 and the new DVPAT) can easily have a development cost of several million dollars and be jealously guarded as a priceless private property by the originator. This, by the way explains, why the best computer programs usually have no written documentation.

Optimality of the Trajectory Shaping Method. Another complication arises from the apparent lack of uniqueness of mathematical trajectory shaping methods: there are many roads to outer space. Some methods are better than others and some completely wasteful. NASA has from the very beginning placed a premium on trajectory shaping elegance. To quote ref. 1: "A non-optimum trajectory is frowned upon, even if it satisfies the mission requirements." In the beginning of the Delta history, the inherent semi-randomness in trajectory optimization methods was one of the main reasons for the almost astronomical number of trajectory runs generated (up to 1600 trajectories per mission).

Eleven years and over eighty launches later, with the advent of the DIGS guidance system, it finally became feasible to utilize an optimum standardized trajectory-shaping technique. Once again the mission analyst was the master of his own fate and the new method was appropriately called BOSS (Baseline Optimum Standardized Shaping). With BOSS a control program could be defined by systematically scaled attitude rates that in general during the test runs resulted in performance being within 5 fps of possible optimum. It not only added up to considerable time and cost savings, but also to better and higher payload estimates.

Maximizing Payload Capabilities. When all is said and calculated, the spacecraft weights sometimes have been known to grow and surpass the vehicle capabilities. What did the desperate Delta mission analysts do in these cases?

In the early years, when the trajectory optimization still had a touch of luck and magic in it, there was sometimes the option of running another 100 trajectory shapings and obtaining another optimum solution perhaps 5 to 10 fps higher (i.e. 1 to 2 lbs. higher) than the DTO. With the present high powered BOSS program this option does not usually exist.

When Delta was young, there was another option of last-minute performance increases: using Air Force surplus stages and having a launch rate of 10-12 vehicles per year, the Delta mission planners were able to grab 'hot off the shelf stages' (i.e. vehicles already scheduled and tested out for Delta that had somewhat higher than average thrust or specific impulse values). Finally, reaching for the last payload pound in the totally exhausted performance barrel, lighter telemetry systems, light batteries, removal of insulation in relatively less important areas, and even leaving the total vehicle unpainted, have come up in the history of Delta.

And in cases where nothing helped, Delta was occasionally known to have an extra card up the sleeve: sudden vehicle improvements.

5) VEHICLE IMPROVEMENTS

The Delta vehicle improvement history and philosophy has been treated in several papers (e.g. ref. 2 and 3). The first improvements of uprating the second and third stages, successively, have already been mentioned.

The basic philosophy of the early Delta stressed flexibility and a "building block" feature. It simply meant to accomodate a wide variety of missions. Delta planners felt free to utilize previously developed improvements, flight proven by other agencies. Delta D, the next improvement, was based on the thrust augmented Thor booster (an Air Force development) and the addition of 3 Castor I solid boosters, almost doubling the old DM-19 capabilities for low circular orbits.

The 26 past Delta configurations are all listed and described in the Delta Restraints Manual (ref. 5). An exhaustive narrative Delta history up to vehicle model 2914 is included in the MDAC Thor history (ref. 3). They all accounted for more than 140 launches, approximately 92% of them successful.

There are four presently available Delta configurations: 3910, 3913, 3914, and 3910/PAM. Also available for mission planning are the four improved second stage versions 3920, 3923, 3924, and 3920/PAM. To get a perspective of the Delta improvement history, let us just tabulate the geosynchronous transfer orbit capabilities for the 14 typical Delta models and the years of their arrival:

1960	Delta	100 lbs
1962	Delta A	150 lbs
1962	Delta B	150 lbs
1963	Delta C	180 lbs
1964	Delta D	230 lbs
1965	Delta E	330 lbs
1968	Delta J	580 lbs
1968	Delta M	785 lbs
1969	Delta M6	1000 lbs
1971	Delta 904	1400 lbs
1972	Delta 2914	1590 lbs
1975	Delta 3914	2100 lbs
1980	Delta 3910/PAM	2540 lbs
1982	Delta 3920/PAM	2890 lbs

Another interesting facet of the Delta improvement history is taking a count of the "Delta building blocks" that have been or will be utilized. First stages have come in four versions: MB-3, Blocks I, II, III, and RS-27. Second stages come historically in seven versions: AJ10-118, AJ10-118A, D, E, F, TRW-201, and AJ10-118K. There have been also seven types of third stages: X-248, X-258, FW-4, TE-364-3, TE-364-4, and PAM.

Last, let us also mention that there have been several Delta improvement proposals that were never approved. Especially dear to the old timers was the old HOSS (Hydrogen-Oxygen Second Stage), that was first dreamed up by Delta mission planners in the mid-sixties, reproposed in the early seventies, and finally build just recently -- by the Japanese!

6) COST HISTORY & THE REIMBURSABLES

The original Delta vehicle, able to launch 100 lbs into a geosynchronous transfer orbit, was priced moderately at roughly \$2.5 M. Five years later Delta's payload capability for the same mission had more than tripled, but the cost was stubbornly kept low, at roughly \$3 M. Thirteen years from the beginning of Delta the payload had risen to 1590 lbs (almost by a factor of sixteen), while the price was slowly rising to \$7 M (by less than a factor of 3). Thus the cost per pound was coming down at a rate really tempting to the non-government (reimbursable) market. A comprehensive history of Delta cost vs. capability is given in ref. 6.

The main result of Delta's low cost and flexible configurations was that certain spacecraft planners sized mission objectives and flight hardware to match available Delta capabilities, rather than consider a larger spacecraft requiring a much more expensive launch vehicle.

Another factor to be considered was the philosophy of the Delta mission planners to actually search out interested spacecraft planners and to widely advertize Delta's performance capabilities. A typical example was the Delta payload planners seminar held at Goddard, which was attended by more than one hundred spacecraft planners, both American and international. Another example was a famous Delta management presentation trip through seven European countries in fourteen days.

Both low cost and vigorous selling seemingly helped. As the Delta old-timers used to joke, Delta was probably the only government operation able to show a profit.

The first privately built satellite was Telstar I, the AT&T Bell Telephone Laboratory's TV satellite in 1962, followed by Telstar II in 1963.

Intelsat F-1, first commercial COMSAT spacecraft with 240 voice channels came in 1965, to be followed by an ever increasing percent of reimbursable launches. Among the private companies, AT&T and COMSAT were followed by RCA and Western Union, all using Deltas to launch their own communications satellites.

Among other United States agencies, Delta was used by the USAF and NOAA (National Oceanic and Atmospheric Administration).

The following foreign governments and agencies have used Delta reimbursable launches:

- European Space Agency (ESA)
- National Space Development Agency (NASDA), Japan
- NATO
- BMFT, Germany
- CNES, France
- Communication Research Center, Canada
- Telesat, Canada
- Indonesian Government (Perumtel)
- Italian Government (CNR)

A box score of Delta reimbursable launches (in launch blocks of 50 each) tells the story of the Delta vehicle as a 'good will ambassador':

Launch numbers	No. of Reimbursables
1 to 50	11
51 to 100	27
101 to 150	34

There have recently been years where 80% to 100% of Delta launches have been reimbursable missions, being a clear statement of Delta's continuing vitality on the space market.

7) FUTURE MISSIONS

An important part of the Delta mission planning philosophy was an active pursuit of future missions. Among the 153 past missions there were payloads originally considering a higher priced brand of launch vehicle. By performing an unsolicited mission analysis, which included tempting short-cuts and extra options, a number of these missions were switched to the "low-price brand". To avoid any hard feelings about the past, let's not mention any names at this point.

On the other hand, various mission analyses ended up in limbo, some of them rather complicated and ambitious. For example, Delta missions to both Mars and Venus were extensively analyzed by the Delta office both in the 1960-s and 1970-s. There were no firm buyers. Similarly, two studies considering Delta as a re-entry test vehicle were conducted by MDAC and Delta Project in the same time frame. Plenty of interest. No sales.

But the noblest moment of the Delta mission analysts was "Operation Kohoutec". In just one week all in-house launch-window and performance capability studies were completed -- for 16 launch dates and 8 arrival dates. Unluckily, the Smithsonian museum was the proud owner of the only spacecraft (capable of such a mission), which they did not want to release from the collections. Luckily, Kohoutec fizzled and there was no great loss for the history of science.

Before passing from these lighter interludes of the Delta mission analysis, let us just observe that presently we have shown Delta payload capabilities for the rendezvous mission with Halley's comet to be in the order of 1480 to 1650 lbs. Puzzlingly, there seems to be a lack of interest in the greatest comet of mankind's history.

Returning to a more serious look to the future of Delta, it must be noted that we presently are experiencing one of the longest mission lineups in our whole history. There are presently listed 40 Delta missions, extending up to the middle of 1985.

The leading customer is RCA with 5 scheduled launches, followed by Telesat (4). Two scheduled launches, each, are lined up by various agencies: Western Electric, AT&T, India, Indonesia, NATO, etc. A number of the 40 launches scheduled for Delta are obviously Shuttle backup and Shuttle overflow types of missions, still capable of picking various options.

8) CONCLUSIONS

Delta, being initially considered only as an interim launch vehicle, has survived for over 21 years and launched over 150 satellites. By following the policy of cost conciousness, aggressive mission/vehicle improvement planning, and 'pleasing the customer', the Delta vehicle has through the years developed into a flexible launch system popular not only in the private sector of the United States, but also in numerous foreign countries and their space agencies. For the past 50 Delta launches, roughly 75% have been reimbursables, a trend seen to be continued in the future. Delta's 40 presently scheduled future missions may well raise the total score to 200, proving that a flexible, expendable launch vehicle system can still remain an active, operational space transportation alternative -- even in the dawning of the Age of the Shuttle.

REFERENCES

1) Van Winkle, D. D., "What Price A Trajectory?" Douglas Memo A2-260-S/AA-62-66, dtd. 1/23/62.

2) Kork, J. and Schindler, W. R., "The Thor-Delta Launch Vehicle: Past and Future," 19th Congress of the International Astronautical Federation, N. Y., Oct. 13-19, 1968; IAF Paper SD32, also "Proceedings of the XIXth International Astronautical Congress," Vol. I, Pergamon Press, 1970.

3) "Thor: The Workhorse of Space -- A Narrative History," MDAC Report MDC G3770, dtd. July 31, 1972.

4) "Delta 1960-1979, 150 Missions, Exploring Space," GSFC Publication, 1979.

5) "Delta Spacecraft Design Restraints," MDAC Report DAC 61687D, dtd. July 1980.

6) Bonnett, E. W., "A Cost History of the Thor-Delta Launch Vehicle Family," MDAC Paper WD 2422, Sept. 1974.