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Research Note to Hypersonic Boost-Glide Weapons by James M. Acton: Analysis of the Boost Phase of the HTV-2 Hypersonic Glider Tests

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"Hypersonic Boost-Glide Weapons," by James M. Acton (this issue), analyzes the portion of the flight of the U.S. HTV-2 hypersonic glide vehicle after it has been boosted to high speed and begins to reenter the atmosphere.[1] To understand more about the HTV-2 test flights that took place in 2010 and 2011, this research note discusses the powered portion of the booster's flight based on simulations from launch through reentry into the atmosphere at about 100 km altitude—the so-called "pierce point." This corresponds to Acton's segments 1 and 2 of the trajectory: boost and exo-atmospheric phases.

This analysis is based on descriptions of the launch vehicle used in the HTV-2 tests, the splashdown points of the booster stages and faring, and the reported speed and altitude of the HTV-2 at the pierce point.

Two test routes were planned for the HTV-2, both starting at Vandenberg Air Force Base in California and ending near Kwajalein Atoll some 7,800 km away. The glide portion of trajectory A stretched essentially straight from the launch to impact point, while trajectory B headed west and then maneuvered during its glide to arc south toward the impact point (see Figure 3 of Acton). While tests were only conducted on trajectory A before the program ended, DARPA released the intended parameters for both trajectories, given in Table 1.

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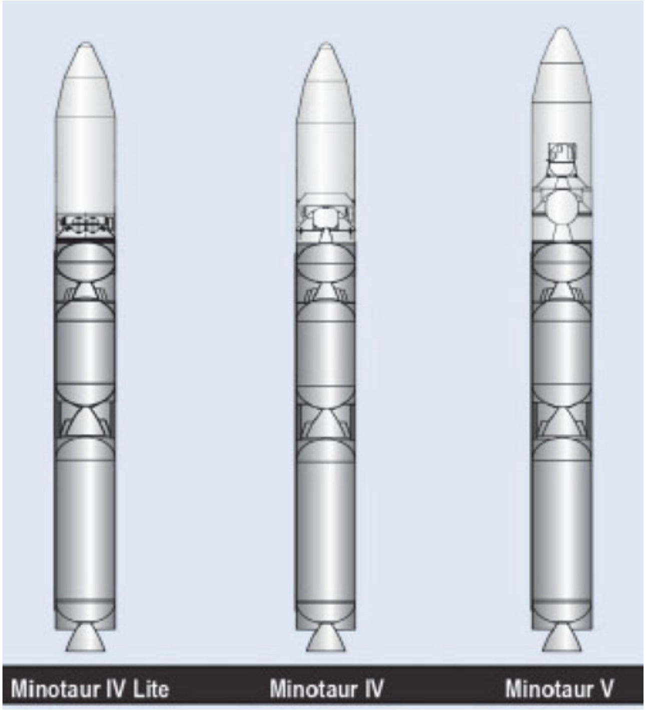

Figure 1: Comparison of the Minotaur 4 and 5 launchers. (Source: Minotaur IV Users Guide http://www.orbital.com/LaunchSystems/Publications/Minotaur_IV_Guide.pdf)

The goal of this analysis is to determine three unknowns: the three-dimensional flight paths of the Minotaur booster on trajectories A and B, and the payload on the launcher, which is the same in both cases. The payload is the mass of the HTV-2 vehicle and the separation device that connects it to the payload adapter. Since the mass of the separation device is expected to be

Figure 2: NOTMAR zones A and B. (Source: Google Earth)

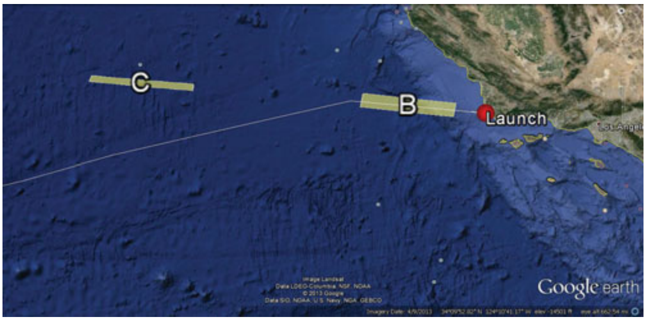

Figure 3: NOTMAR zones B and C. The white line is the approximate ground path followed by Trajectory A. (Source: Google Earth)

only 10 to 20 kg, the payload mass will essentially be the HTV-2 mass to the accuracy of the calculations.[2]

The flight trajectories are calculated with a computer program that integrates the equations of motion of the launcher on a round Earth with a realistic atmosphere model (see Technical Note). The Minotaur is launched vertically and the trajectory is controlled by varying the direction of thrust relative to the velocity.

The inputs to the calculation are the parameters of the Minotaur booster and the locations of the splashdown zones for the Minotaur stages. The analysis requires an iterative process of varying the payload mass, and for each mass seeing if it is possible for the booster to follow a trajectory that drops the Minotaur stages in the zones announced for the test and delivers the HTV-2 to the pierce point with the parameters given for both trajectories A and B.

Table 1: This table gives the "pierce point" conditions for the two trajectories on which DARPA planned to test the HTV-2. The pierce point appears to correspond to an altitude of 100 km. The negative sign in front of the angles means that these angles are below the horizontal. (Source: Acton, Figure 3 and http://commons.wikimedia.org/wiki/File:FalconHTV2FlightPath.jpg).

	Trajectory A	Trajectory B
Time	435 s	376 s
Velocity	19,700 fps = 6.00 km/s	23,500 fps = 7.16 km/s
Angle	-3 deg	-5.03 deg

Table 2: Parameters for the Minotaur stages, in meters (m), metric tonnes (t), and seconds (s). To be consistent with the other parameters in the table, the sea-level value of specific impulse for the first stage appears to be 259 s, rather than 229 s as listed in the source. While these values vary somewhat between sources, those variations are within the accuracy of the analysis in this paper. (Source: http://www.spacelaunchreport.com/mintaur4.html)

Stage	1	2	3
Engine	SR-118	SR-119	SR-120
Booster Diameter	2.34 m	2.34 m	2.34 m
Propellant mass	45.37 t	24.49 t	7.07 t
Total mass	48.99 t	27.67 t	7.71 t
Specific impulse	259 s (sea level) 282 s (vac)	309 s (vac)	300 s (vac)
Thrust	209 t (sea level) 226.8 t (vac)	124.7 t (vac)	29.48 t (vac)
Burn time	56.4 s	60.7 s	72 s

THE BOOSTER FOR THE HTV-2 TESTS

The booster for the HTV-2 tests was the Minotaur 4-Lite launch vehicle, which uses the first three stages of the solid-fueled Peacekeeper intercontinental ballistic missile (ICBM).[3] Parameter values for the Minotaur stages are given in Table 2.

The mass of the payload fairing, which covers the payload at launch and is dropped early in flight, is approximately 450 kg.[4] The remaining structural mass of the launcher, which includes various interstage structures, the Guidance and Control Assembly, the Payload Adaptor Module, and other hardware, can be estimated by considering the mass breakdown of the Minotaur 5, which includes two small upper stages. NASA gives the liftoff mass of the Minotaur 5 as 89.37 t, which includes a payload of 0.38 t.[5] Subtracting the mass of the stages[6] and fairing gives the additional structural mass as 0.86 t. Figure 1 shows that the structure of the Minotaur 4-Lite is similar to that of the Minotaur 5, so the structural mass of the Minotaur 4-Lite is assumed to be roughly 0.8 t. Since the inputs used to determine this mass are not all from the same source and include some natural variability, this value must be considered approximate.

Methodology

As noted above, DARPA's descriptions of the HTV-2 test program indicate that it planned tests along two different routes between the launch in California and impact in the ocean near Kwajalein Atoll. Launches took place from Space Launch Complex (SLC) 8 at Vandenberg Air Force Base in California. For the 22 April 2010 launch, a Notice to Mariners (NOTMAR) was issued that

Table 3: This table gives the approximate distance of the two ends of each NOTMAR zone from the launch point.

Zone	Distance of Zone Ends from Launch Point
A	0–30
B	60–250
C	570–780
D	2300–3600

listed four zones off the coast near SLC-8 where debris from the launch was expected to fall into the ocean.[7] The first three zones (A, B, C) are shown in Figures 2 and 3.

Zone A, which reaches out to about 30 km from the launch site, appears to be for the first stage casing (see Table 3).

The large size of zone B, which reaches from about 60 to 250 km from the launch site, appears to be for the payload fairing since the fairing's large surface-to-mass ratio would cause it to be strongly affected by the atmosphere as it fell to Earth, leading to a large uncertainty in its impact location. This would imply that the fairing was released relatively early during the burning of the second stage, which is typical for launches so that the rocket motors have less mass to accelerate.[8]

Zone C appears to be the splashdown zone for the second stage casing. Figure 4 shows zones B, C, as well as zone D, which appears to be for the third stage casing and lies near the Hawaiian Islands. What is clear from this figure is that for this test, which follows trajectory A, the Minotaur second stage continued along the initial direction of the launch and the third stage is used to rotate the trajectory by about 16 degrees from that direction, putting the HTV-2 on a relatively direct path toward its intended splashdown point near Kwajalein Atoll. This rotation is referred to below as the dogleg maneuver.

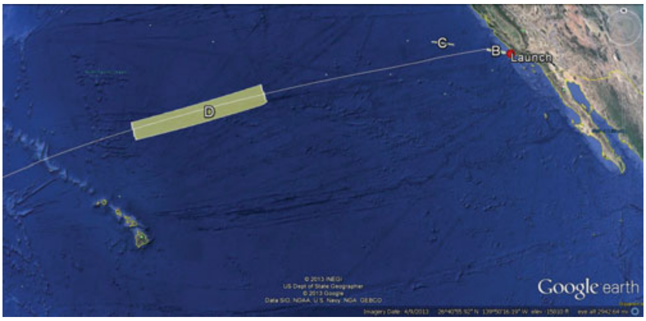

Figure 4: NOTMARs B, C, and D for Trajectory A. (Image from Google Earth)

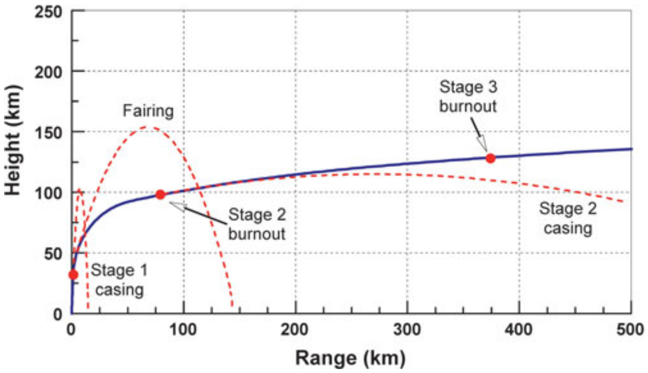

Figure 5: This plot shows the boost phase of the Minotaur on trajectory A (solid line), the stage burnout locations (dots), and the trajectories of the empty first and second stages and the payload fairing (dashed lines).

The approximate ground path of the booster is indicated by the white line in Figures 2, 3, and 4.

Descriptions of the tests state that the Minotaur booster provides more speed than is needed for trajectory A and that “energy-management maneuvers” are required to reduce the speed at the end of boost phase,[9] so the third-stage dogleg maneuver would provide a way to reduce the energy on trajectory A.

For the planned flight along trajectory B, the launch appears to follow the same ground path as trajectory A early in flight but then continues along that same direction throughout boost phase. The direction of the early part of the flight may have been designed with trajectory B in mind. The splashdown zones for trajectory B were never released; for this analysis, we assume zones A, B, and C are the same as those announced for trajectory A.

BOOST ANALYSIS

The iterative analysis described above, using the Minotaur booster with the parameters given in Table 2, indicates that the mass of the HTV-2 is approximately 1,000 kg. The trajectory calculations discussed below use this mass.

The first-stage drop zone is so close to the launch site that this stage must travel nearly vertically, which allows the booster to gain altitude quickly (Figure 5). Simulations give a burnout angle of about 87 degrees (3 degrees from vertical), with a burnout speed of 1.4 km/s and an altitude of 32 km.

During second-stage burn, the booster begins to turn to flatten the trajectory. It burns out at an angle of about 10 degrees at a speed of 3 km/s (Figure 5).

The results are not very sensitive to the timing of the release of the fairing, which must occur during second-stage burn if drop zone B is for the fairing. For this simulation, the fairing must be released when the booster reaches 50 km altitude in order for it to fall near the center of the drop zone (this occurs at 69 s into flight). The booster's speed is only 1.5 km/s at the time of release, so the dynamic pressure (ρV^2) is only 1% of its maximum value (max Q), which occurs at an altitude of 11 km. As a result, releasing the fairing at that time should not cause problems for the payload. Releasing the fairing when the booster reaches 60 km altitude would cause the fairing to land at the far end of the drop zone; releasing later than that would cause it to land beyond the drop zone.

The flyout curve shown in Figure 5 is the same for trajectories A and B through stage 2 burnout.

Trajectory A

For trajectory A, we must estimate the amount of energy used to rotate the plane of the trajectory through 16 degrees to give the dogleg maneuver shown in Figure 3. The total capability of a rocket stage to accelerate—to increase the speed or maneuver—is described by the delta-V, or ΔV, of the stage. The total ΔV of the third stage of the Minotaur is:[10]

$$\Delta V = g_0 I_{sp} \ln\left(M_i/M_f\right). \tag{1}$$

where M_i is the mass of the stage plus payload at the beginning of stage 3 burn, I_{sp} is the specific impulse of the rocket motor, M_f is the mass of the stage plus payload at the end of stage 3 burn, and $g_0 = 9.8$ m/s. In this case $M_i = 7.71 + 0.8 + 1.0 = 9.51$ tonnes and $M_f = M_i - 7.07 = 2.44$ tonnes, where 7.71 and 7.07 are, respectively, the total mass and the propellant mass of stage 3 (see Table 1), 0.8 is the additional structural mass of the booster, and 1.0 is the payload mass. Using $I_{sp} = 300$ s, Eq. (1) gives $\Delta V = 4.0$ km/s. Since at this point the trajectory is essentially horizontal, losses due to gravity are negligible and all of the ΔV is available for increasing the speed and maneuvering.[11]

The ΔV required for an object moving at speed V to change the direction of its velocity by an angle θ is given by:[12]

$$\Delta V = 2V \sin(\theta/2). \tag{2}$$

As noted, the dogleg maneuver corresponds to $\theta = 16$ degrees. For trajectory A the velocity of the stage increases from 3 to 6 km/s during stage 3 burn. Eq. (2) shows that less ΔV is required if the maneuver occurs at lower V, so the maneuver is assumed to take place by applying lateral thrust during the first part of the stage 3 burn—when the velocity of the stage is between $V = 3$ and $V = 4.5$ km/s. Using the average speed $V = (3 + 4.5)/2$, Eq. (2) gives $\Delta V = 1.0$ km/s for the maneuver.

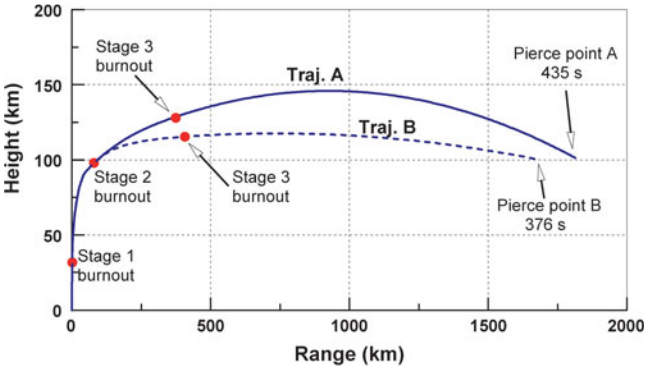

Figure 6: This plot compares trajectories A and B from launch to the pierce point (100 km altitude) for each trajectory. Note that the vertical scale is stretched compared to the horizontal scale, which exaggerates the difference in reentry angle between the two trajectories at the pierce point.

This result shows that approximately one-quarter of the total ΔV of the stage is required for the dogleg maneuver. In calculating the boost phase of trajectory A, the thrust of stage 3 is therefore reduced by a factor of 25% to account for the energy used in the maneuver.

The trajectory calculations show that including this maneuver can produce a trajectory that gives the pierce point conditions in Table 1 for trajectory A at 435 s after launch, and that this occurs at a range of about 1800 km from the launch site. This trajectory also gives splashdown points for the Minotaur stages and fairing in the stated NOTMAR zones.

In this case, stage 3 burns out with a speed of 6.0 km/s with an elevation angle of 3.7 degrees and an altitude of 123 km. The third stage casing splashes down at a range of 2500 km.

Trajectory B

Trajectory B is assumed not to use energy-management maneuvers to shed energy. In this case, stage three burns out with a speed of 7.1 km/s with an elevation angle of 0.8 degrees and an altitude of 110 km, and leads to the dotted curve in Figure 6. The third-stage casing splashes down at a range of 3200 km.

The trajectory calculations show that this trajectory gives the pierce point conditions in Table 1 for trajectory B at 376 s after launch, and that this occurs at a range of about 1700 km from the launch site. This trajectory also gives splashdown points for the Minotaur stages and fairing in the stated NOTMAR zones.

CONCLUSION

These calculations show that using parameters for the Minotaur 4-Lite booster and the locations of the splashdown zones for the rocket stages given by the NOTMAR for the April 2010 test, it is possible to find boost trajectories that give the pierce point conditions announced by DARPA for both trajectories A and B.

Moreover, these calculations imply that the HTV-2 glider has a mass of approximately 1,000 kg at launch.

As noted above, these calculations assume that trajectory B does not require energy-management maneuvers and that the only such maneuver required for trajectory A is the dogleg maneuver. If, however, the combined mass of the HTV-2 and booster structure is significantly less than assumed above, additional energy-management maneuvers may be required for both trajectories, which would then be more complicated than the simple shapes shown above.

TECHNICAL NOTE

Because the focus of this paper is on the launch trajectory only in the early part of flight, the calculations can use the equations of motion for the booster on a round, non-rotating Earth with an atmosphere.[13] The thrust of the first stage will vary with altitude due to the change of atmospheric pressure at the opening of the engine nozzle:

$$T(h) \;=\; T(0) \;+\; A_{Nozzle}(p(0) - p(h)). \tag{3}$$

where A_{nozzle} is the nozzle area, $T(h)$ is the thrust at altitude h, and $p(h)$ is atmospheric pressure at altitude h. The values of thrust for the first stage in Table 2, along with $p(0) = 101{,}325$ kg/s^{2}m at sea level and $p(vacuum) = 0$, can be used to determine $A_{nozzle} = 1.7$ m^2.

NOTES AND REFERENCES

1. James M. Acton, "Hypersonic Boost-Glide Weapons," *Science & Global Security, 23,* (2015): 191–219.

2. Orbital Science Corporation's Users Guide for the Minotaur, Table 2.5.2-1, 57, June 2013, http://www.orbital.com/LaunchSystems/Publications/Minotaur_IV_Guide.pdf.

3. T. Huynh and J. Kriz, "Final Environmental Assessment for Hypersonic Technology Vehicle 2 Flight Tests," 28 April 2009, http://www.dtic.mil/get-tr-doc/pdf?AD=ADA544343.

4. Spaceflight 101, "Minotaur V Launch Vehicle Information," http://www.spaceflight101.com/minotaur-v-launch-vehicle-information.html.

5. This is from the NASA press kit for LADEE mission, and is for the version of M-V with the Star 48BV and Star 37FM upper stages: http://www.nasa.gov/sites/default/files/files/LADEE-Press-Kit-08292013.pdf.

6. For the Minotaur V this includes the mass of two additional stages: 2.16 t for the Star 48VB and 1.15 t for the Star 37FM (see ATK Space Propulsion Products Catalog, http://www.atk.com/wp-content/uploads/2013/02/ATK-Motor-Catalog-2012.pdf.)

7. Notice to Mariners, 1 May 2010, 111.1–10, http://msi.nga.mil/MSISiteContent/StaticFiles/NAV_PUBS/UNTM/201018/NtM_18-2010.pdf

8. This timing disagrees with a DARPA animation of segments of the launch, which shows the payload fairing being jettisoned late in boost phase, shortly before the HTV-2 separates from the upper booster stage; see http://www.darpa.mil/Flight%20Overview%20slide–UPDATED%20as%20of%2029%20Jul%2011.html.

9. G. Warwick, “DARPA’s HTV-2 Didn’t Phone Home,” *Aviation Week* Blog, 24 April 2010, http://www.aviationweek.com/Blogs.aspx?plckBlogId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7 Post:70769585-4348-4701-889a-f02c58f38314.

10. D. Wright, L. Grego, and L. Gronlund, “The Physics of Space Security,” *Union of Concerned Scientists, 75*, 2005. http://www.ucsusa.org/nuclear_weapons_and_global_security/solutions/space-weapons/the-physics-of-space-security.html.

11. As a check, the calculation of trajectory B shows that during third stage burn the speed of the stage increases by 4 km/s.

12. Wright et al., 64.

13. See Appendix B of L. Gronlund and D. Wright, “Depressed Trajectory SLBMs,” *Science and Global Security 3* (1992): 101–159, http://scienceandglobalsecurity.org/archive/sgs03gronlund.pdf.