S19 Guidance of the Black Brant X Sounding Rocket

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For the first time, a three-stage sounding rocket [Black Brant X (BBX)] has been equipped with the S19 guidance system. The system is located on top of the second stage and keeps the attitude of the vehicle constant during the first 18 s of flight. At third-stage ignition, the S19 ensures a very small trajectory dispersion, i.e., the payload impact dispersion mainly depends on the coning of the third stage. Thus a substantial reduction of the impact dispersion is achieved while the apogee performance is basically unchanged. Three S19-BBX vehicles have been successfully launched. According to telemetry signals that have been compared to postflight simulations, the S19's have worked nominally during all three flights. A minor miscalculation of total vehicle aerodynamics was also revealed, which will affect the wind limits of future flights somewhat.

Introduction

DURING the era of sounding rockets there has been a permanent demand for larger and more powerful rockets with the capability to deliver very heavy payloads to very high apogee altitudes. The BBX vehicle is the latest response to this demand. It was jointly developed by NASA Goddard Space Flight Center, National Research Council of Canada, Bristol Aerospace Ltd., Swedish Space Corporation, and Saab-Scania Corporation. The large inherent impact dispersion of such a high-performance vehicle has been highly reduced by the use of the Saab-SSC-S19 guidance system.

The guidance system initially was designed for a single-stage Black Brant VC rocket.[1,2] It has since been utilized for the control of larger vehicles, where aerodynamics and other design parameters have varied considerably from one rocket to another. The BBX is the extreme in terms of mass, inertia, launch tip-off transient, and bending mode frequency. This paper describes the adaption of the standard S19 to the BBX, some properties of the guided vehicle, and some results of a postflight evaluation.

The Standard S19

The standard S19 is a completely self-contained module which can be integrated into a payload without interfering with other subsystems of the payload. The system is tested and operated prior to launch from a lightweight launch console called the control box, which is connected to the module via an umbilical. During flight several monitor signals are available both for scientific use (vehicle roll, pitch, and yaw orientation) and internal functional checkout.

Refurbishment of the S19 is a standard procedure if the payload is recovered. The weight of the guidance module is 33 kg (73 lbs), the length 0.4 m (15.7 in.), and the diameter 0.428 m (17.26 in.).

The function of the S19 is as follows: A gyro platform measures the roll, pitch, and yaw attitudes of the vehicle with respect to the launcher. This information is used to maintain the vehicle at a constant lateral attitude (equal to the attitude of the launcher) during the first period of flight. The control period starts at launch and ranges from 8 to 18 s depending on the vehicle, and thus a several kilometer long launcher rail is simulated. The roll orientation of the vehicle is not controlled. The gyro roll information is used only to transform the inertially referenced autopilot commands into body-fixed commands for two pneumatic servos, each of which is connected to two control surfaces (canards). The guidance period is terminated by mechanical decoupling of the canards, allowing them to align with the airstream and, thus, causing no more lateral forces on the vehicle. Figure 1 shows the guidance loop briefly described above.

Some advantages of using the system follow.

Low Impact Dispersion

The influence of low-altitude winds and thrust misalignment is effectively reduced. A typical 1σ impact dispersion figure is 0.02 km/km apogee for an 8.5 m (28 ft) rail launch. If a Nike-Black Brant VC vehicle is used as an example, the dispersion reduction is six times when comparing an unguided to a guided rocket.[3] The impact area of course is reduced by the square of this figure. At ranges where the admissible impact area is limited, this means that more powerful rockets may be used in order to reach higher apogees.

Faster Launch Campaigns

Range safety restrictions on wind velocity, wind directions, and wind variability normally make it harder to launch an unguided vehicle at a given instant, e.g., when the scientific conditions are "go." A study performed during a launch campaign at Esrange, Sweden, in 1979 showed a range safety "go" during 12 days out of 13 for the two S19-guided BBVC's. Without guidance these BBVC's would have been "no go" all 13 days.[4] (The scientific conditions were "no go" until day 13, when the rockets were successfully launched.)

For the BBX vehicle described in this paper, however, the head wind limit is not necessarily improved by the guidance, as will be shown later.

Accurate Trajectory

An accurate trajectory is scientifically valuable in many cases. Hitting a magnetic field line of interest or staying in the shadow of the moon during a solar eclipse is more likely when S19 guidance is used.

Autopilot Design

Open-loop Bode plots for the guidance loop of the BBX are shown in Figs. 2-4. They include gain and phase curves just prior to booster burnout ($t+4.35$ s), after booster separation

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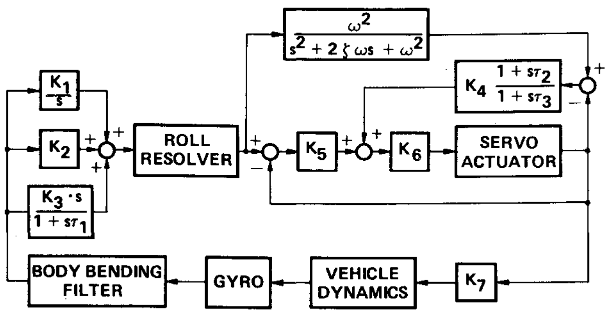

Fig. 1 Guidance loop.

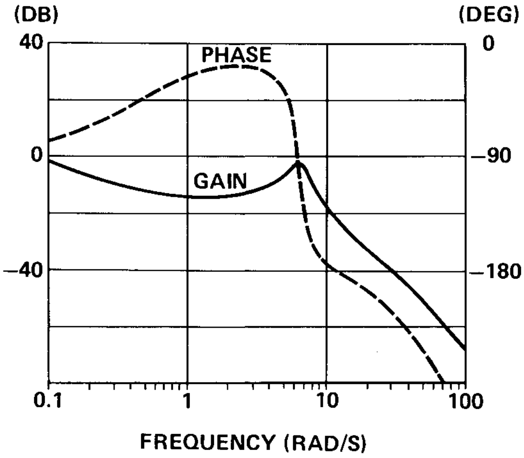

Fig. 2 Stability diagram at $t+4.35$ s.

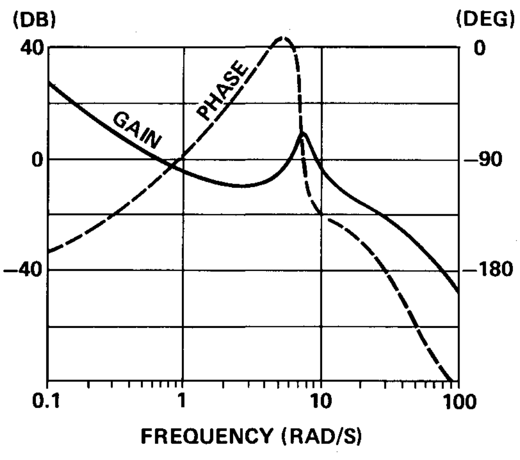

Fig. 3 Stability diagram at $t+5$ s.

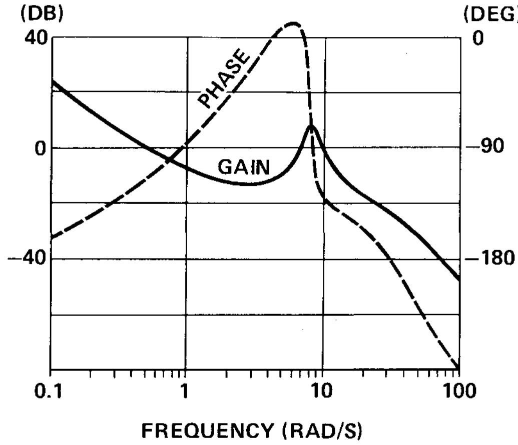

Fig. 4 Stability diagram at $t+12$ s (including first bending mode).

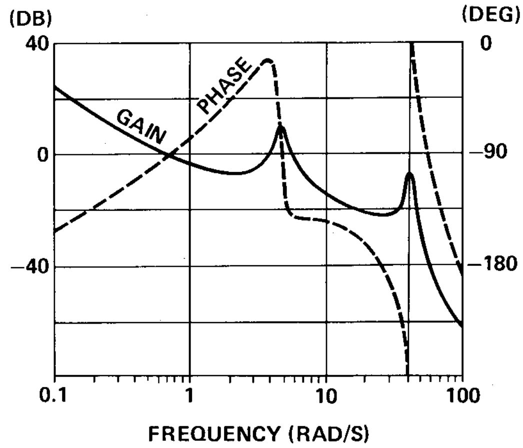

Fig. 5 Stability diagram at $t+18$ s.

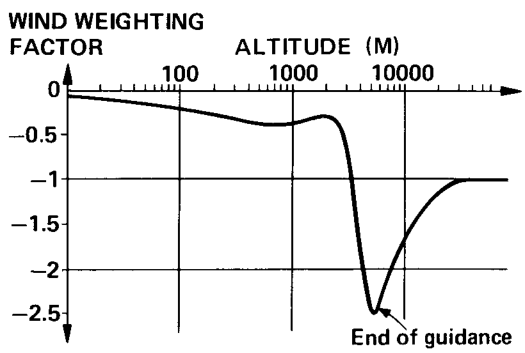

Fig. 6 Third-stage wind weighting factor.

($t+5$ s), and at sustainer ignition ($t+12$ s). The diagrams are based on dynamical models of all hardware and also include aerodynamic response. At $t+4.35$ s the gain is somewhat low, but it can not be increased due to a low static phase margin that appears just after booster burnout (this is not visible in the diagrams). The low phase margin only lasts for 0.4 s nominally, i.e., from booster separation time until the autopilot gains are changed. The body bending mode stability margin is very high during the boost phase. [Note: A static phase margin of around 45 deg is considered a design goal in this application (equivalent to a damping of 0.7 in a second-order system).]

During the coast and sustain phases the gain cannot be improved either, since the static phase margin is 50 deg at $t+5$ s. Increasing both phase and gain using more lead compensation has adverse effects on the body bending mode stability margin. Figure 4 includes the first body bending mode at $t+12$ s.

Compared to the Nike-BBVC applications, however, the time of guidance may be extended. This is obvious in Figure 5, which shows that the stability properties are almost identical at $t+5$ and 18 s. Since the sustainer is not ignited until $t+12$ s, thrust misalignment of the motor is taken care of better if the guidance lasts until $t+18$ s. It was decided to take advantage of this possibility and, thus, the gas bottle that energizes the S19 servos was increased to allow for guidance during 18 s. This hardware change is now part of all newly produced S19's.

Table 1 Trajectory characteristics

Parameter	Value
Apogee altitude, km	682
Time at apogee, s	461
Range at apogee, km	378
Impact range (3rd stage), km	781
Impact range (2nd stage), km	141
Burnout velocity (3rd stage), m/s	3256
Burnout velocity (2nd stage), m/s	1621
Altitude at end of guidance, km	5.5
Altitude at 3rd stage ignition, km	84
Velocity at 3rd stage ignition, m/s	1263
Max dynamic pressure, kN/m^2	116

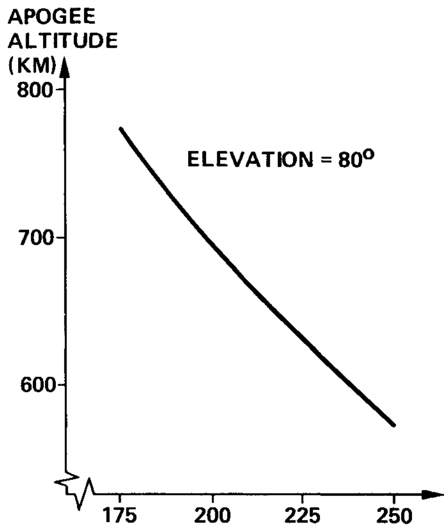

Fig. 7 Apogee vs payload weight.

In conclusion, the BBX autopilot is identical to the one used on previous Nike BBVC's. The guidance time is extended to 18 s.

Wind Weighting

In order to achieve a nominal trajectory, the launcher azimuth and elevation angles must be corrected for the wind disturbance. The wind velocities at different altitude intervals are measured using radar or optically tracked balloons. By multiplying these winds with the so-called wind weighting factor, a corresponding ballistic wind is calculated. This wind is a true measure of the wind disturbance and thus can be used to determine the size and direction of the launcher correction.

The third-stage wind weighting factor is shown in Fig. 6. The shape of the curve is characteristic for any S19-equipped sounding rocket. The curve has a peak at end of guidance altitude. The rather big value at the peak does not mean that the guided rocket is more sensitive to wind than an unguided rocket, since the unit wind effect is much lower for the guided rocket.

As can be observed, the wind weighting factor is negative. The sign is determined by the behavior of a guided rocket when subjected to a wind disturbance. The guided rocket maintains a constant lateral attitude (the launcher attitude) and therefore drifts with the wind, while an unguided vehicle points into the wind causing an orbital disturbance which is much larger than the drift of the guided vehicle.[2]

Regardless of what has been stated previously, the wind weighting procedure is exactly the same for an S19-guided rocket as for an unguided rocket. Note, however, that the result of the wind weighting will be a launcher correction in opposite directions in the two cases. The launcher correction also is smaller in the guided case, normally much smaller.

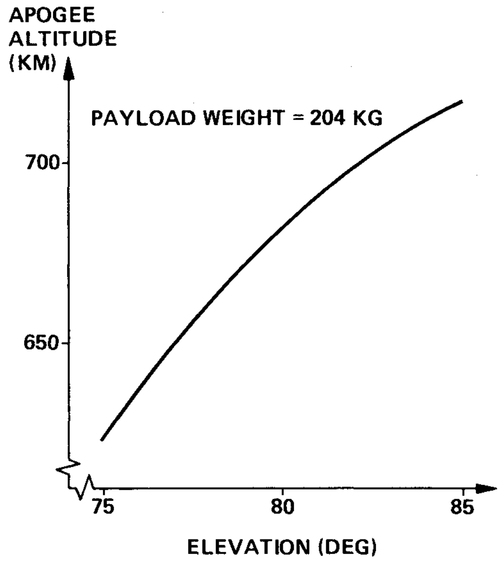

Fig. 8 Apogee vs elevation.

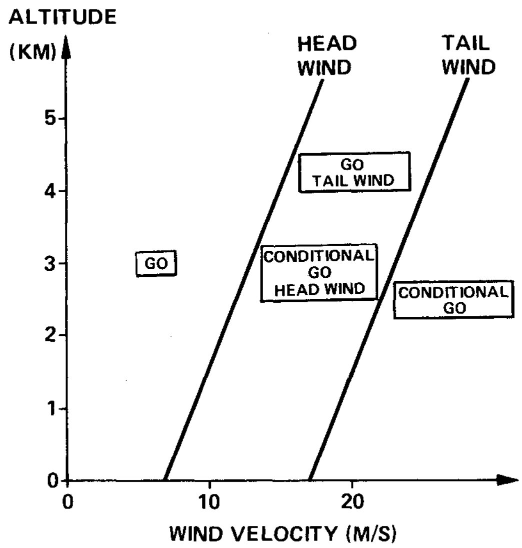

Fig. 9 General wind limit.

For a payload weight of 204 kg (450 lb) and at QE = 80 deg, third-stage wind weighting data for the BBX are: unit wind effect = 4.32 km/m/s (2.22 km/knot); tower tilt effect = 72.8 km/deg; and launcher correction = 0.059 deg/m/s (0.030 deg/knot).

It is also of interest to present the wind weighting parameters of the second-stage payload, which reaches an apogee of 161 km and an impact range of 141 km, since they are typical for a two-stage Terrier-BBVC with a 682kg (1504 lb) payload: Unit wind effect = 0.826 km/m/s (0.425 km/knot); tower tilt effect = 13 km/deg; and launcher correction = 0.064 deg/m/s (0.033 deg/knot).

The wind weighting factor vs altitude is very similar to that of the third stage (Fig. 6).

Trajectory Data

Assuming a round, nonrotating Earth and using a three-degree-of-freedom model during third-stage burn, the BBX trajectory has been calculated. Some parameters are shown in Table 1.

Table 2 Flight-path angle errors at second-stage separation

Error source	Error, deg
Launcher pointing	0.173
Mounting of rocket on launcher	0.173
Mounting of S19 and gyro	~0
Uncage disturbance	~0
Gyro pickoff error	0.139
Gyro drifts:	
g insensitive	0.117
g_2 sensitive	0.235
g sensitive	0.049
Vibration induced drift	0.148
Steady wind (1 m/s)	0.249
Wind gusts ($\sigma = 1$ m/s, all axes)	0.031
Thrust misalignment (1st and 2nd stages)	0.089
Total (root sum square)	0.493

Figure 7 gives the apogee performance vs payload weight at a launcher elevation of 80 deg, and Fig. 8 gives the apogee performance vs launcher elevation at a payload weight 204 kg. It might be pointed out that the reduction of apogee due to the weight and drag of the S19 is only 4% or 30 km since it is separated along with the second stage.

Wind Limits

The wind weighting is valid only below the canard stall limit. This gives some wind restrictions for the vehicle which have to be calculated. Figure 9 gives a general wind limit. There is a "go" area which means that the wind weighting in Fig. 6 is valid and there is a "conditional go" area where it might be valid depending on the direction and the shape of the wind profile from ground up to the end of guidance altitude. Several other wind limit profiles can be calculated that fulfil the stall angle limit, for instance, a higher ground wind can be tolerated if the wind above 1 km is low, etc. Figure 9 is valid for launch elevation of 80 deg. If the elevation is higher, the head and tail wind limits will get closer to each other.

Generally, the aftward positioning of the S19 within the payload is less favorable from wind limit and performance points of view. In the BBX case, however, the lower wind limits were accepted since placing the S19 in the third-stage payload would have reduced the apogee significantly.

According to Ref. 6 the allowable ground wind for an unguided BBX with the same length would be 6.9 m/s. For the BBX, this means that the head wind limit in some cases is not improved by using the S19, while the tail wind limit is improved considerably.

Dispersion

The impact dispersion for the guided BBX can be divided into two main parts. One is related to the coning angle at third-stage ignition and third-stage thrust misalignment. That part is not dealt with in this paper since it is independent of the S19. The other part is related to the trajectory dispersion prior to third-stage ignition. This dispersion consists of a number of small contributions as listed in Table 2 (1σ values).

Some error sources, such as launcher pointing error, mounting error of rocket on launcher, uncage disturbance, and gyro pickoff error are present from launch, while others, such as gyro drift,[7] build up during guidance. In Table 2, however, all errors are transformed into second-stage separation time equivalents. This serves two purposes: first, the relative sizes of the error sources can be compared and, second, a total flight-path angle error can be calculated (root of sum of squares). The transformation is very straightforward and utilizes the relationship of trajectory tilt derivatives at three times: 1) at launch 72.8 km/deg (= tower tilt effect), 2) at end of guidance 69.0 km/deg, and 3) at second-stage separation 42.0 km/deg.

The derivatives translate a flight-path angle change into an impact point change. An angular error at launch time is then expressed at second-stage separation time simply by multiplying by 72.8 and dividing by 42. The remaining errors (steady wind excluded) were determined by six-degree-of-freedom simulations until end of guidance time. The resulting flight-path angle errors then were transformed with the factor $69/42 = 1.64$.

As the influence of a steady wind is known (within the wind limits) through the wind weighting procedure, only wind prediction errors need to be considered in the dispersion analysis. The figure in Table 2 is deduced from the wind weighting factor diagram (Fig. 6) and the unit wind effect. An intermediate impact error was calculated between the results of two cases: first, a wind error of constant direction at all altitudes and, second, a wind error that changes direction by 180 deg at end of guidance altitude. The error then was transformed into a flight-path angle error using the proper tilt derivative.

The impact performance of the second stage is now easily calculated by multiplying the total error of 0.493 deg by the tower tilt effect for the second stage at second-stage separation which is 7.5 km/deg, and RSS-adding to this the thrust, weight, and drag errors of the vehicle. The 1σ estimation of the latter errors is 2 km. Since they only appear in the downrange direction, the total impact dispersion for the second stage is:

$$\sqrt{(0.493 \times 7.5)^2 + 2^2} = 4.3 \text{ km downrange}$$

$$0.493 \times 7.5 = 3.8 \text{ km crossrange}$$

As stated earlier, the third-stage impact dispersion depends mainly on the coning and thrust misalignment of the third stage. The S19-dependent part of the dispersion is only $0.493 \times 42 = 20.7$ km (1σ).

Launch Campaigns

The newly developed BBX rocket was flown for the first time on Aug. 14, 1981 from Wallops Flight Center. The objective of the test flight was to demonstrate the performance of the BBX and its subsystems. The flight was a great success with a performance that was close to nominal.

The test and integration of the S19 went smoothly and the flight was another success for the system, which performed nominally. The support and the S19 system itself was rendered to NASA by the Swedish Space Corporation. It is also interesting to note that this was the second refurbished module flown (previously flown and recovered at Esrange, Sweden).

During the Centaur campaign at Cape Parry, North West Territories (NWT), Canada, five sounding rockets were launched, the first and last of these being BBX vehicles.[8] The BBX flights were the first two operational ones. They were launched on Nov. 30 and Dec. 13, 1981. Both were equipped with NASA-owned S19 guidance systems. The S19's (and the one at WFC) were tested and preparated completely separate from the payload, which again stresses what was said earlier about the independent, noninterfering nature of the S19.

Both S19 units worked nominally during the launches. The impact dispersion of the first flight was within the 3σ limits, while the dispersion of the second one was outside, though still within the impact area of the range. The latter was partly caused by an anomaly of the S19 aerodynamic data, partly by third-stage coning or motor thrust misalignment both acting in the same direction.

Postflight Simulations

For all three BBX launches postflight simulations have been carried out. Conclusions to be made from these simulations concerning the S19 are:

1) Canard efficiency is about 10% below calculated data.

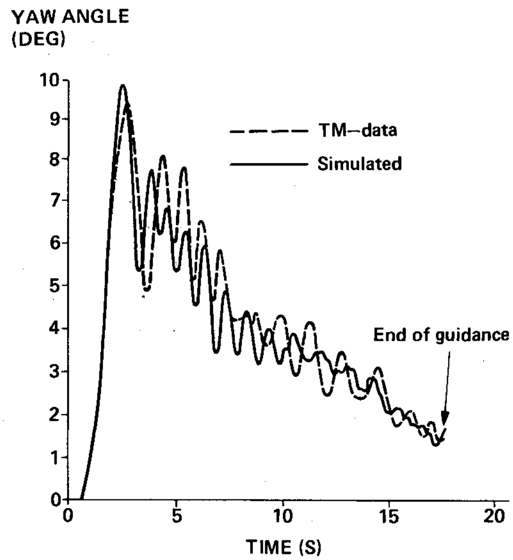

Fig. 10 Yaw angle third launch.

2) Maximum allowable total angle of attack at canard surface is 5-10 deg lower than calculated.

The launches are referred to as 1, 2, and 3 meaning test flight from Wallops Flight Center, first launch from Cape Parry, and second launch from Cape Parry, respectively.

The telemetry signals show a nominal behavior at launch 1. The initial attitude transient in the flight data from the gyro suggests a booster thrust misalignment close to 3σ (3.5 mrad). The later part of the guidance phase data confirms the 10% canard efficiency reduction mentioned previously. It is impossible to determine the thrust misalignment of the second-stage motor by comparing flight data and postflight simulations. The rocket was launched while having moderate tail winds well within wind limits.

At launch 2 gyro pitch and yaw signals indicate a 1.5σ booster thrust misalignment. Similar to launch 1, the canard angles are smaller in the postflight simulations. Reducing the canard efficiency by 10% gives a good agreement. Between $t+9$ s (time from where radar data are available) to end of guidance at $t+18$ s the velocity is 10% lower than expected. At launch time, there were tail winds of moderate strength. The wind caused no trouble and was well within the wind limits.

Since second-stage impact was not measured, the impact dispersion is not known. According to radar data just before second-stage separation the S19 kept flight-path angles within specification.

Launch 3 is the most interesting case, since the S19 canards were saturated during a 6-s period. In itself, that is not a problem, but the flight was not nominal even though the winds were just within the calculated wind limit when the last wind profile was measured and the S19 worked nominally. At the time there was a dominating sidewind component. This resulted in a flight-path angle error of 1.8 deg compared to the expected trajectory.

The canards were saturated between $t+9$ and 15 s. This was foreseen in the calculations but since the canard efficiency and the stall limit was lower than expected, the yaw angle was influenced in an unexpected way causing the flight-path angle error. Figure 10 shows the yaw angle achieved in a postflight simulation with the following input data: thrust misalignment $= 1.5\sigma$, canard efficiency reduced 10%, and canard stall angle reduced 8.5 deg.

This gives good correspondence with the telemetry signals. A small reduction of the wind limits will probably be required for future flights with similar configurations.

Because the precalculated wind limit was too large, the rocket was actually launched in a wind condition outside the real wind limit. Canard stalling has not been experienced on previous S19 flights. It is interesting to note that this phenomenon is by no means devastating for the flight but merely causes a gradual degradation of the performance.

Conclusions

The adaption of the standard S19 to the BBX and the performance of the vehicle has been presented. By evaluating the postflight information from three BBX launches it can be concluded that the S19 guidance module is suitable for guiding the BBX three-stage sounding rocket. For the first time the S19 canards were both saturated and stalled during flight which has given valuable information about the behavior in such cases. When launched within the wind limits set by canard stalling conditions, the guidance effectively decreases the impact area compared to the unguided rocket.

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