GUIDANCE, NAVIGATION & CONTROL SYSTEMS. REVIEW, ANALYSIS AND FUTURE DESIGNS

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ABSTRACT

Systems for guidance, navigation and control (GNC) of sounding rockets have long been produced by RUAG Aerospace Sweden AB, with the inaugural flight of a prototype S19 boost control system successfully performed on 10 Jan, 1976. The main objectives of the GNC systems are to reduce the impact dispersion of the re-entering vehicle, and to make it possible to launch under most all wind conditions, thereby reducing launch campaign costs.

This paper first describes the various GNC generations and discusses the reasons for each development, as well as the performance of the systems in relation to the requirements laid down by the user. Finally, a look into the future is made in order to identify possible bases for next generation system solutions, and the user benefits implied by such solutions.

1. THE BEGINNING

Almost fifty years ago, the advantages of using sounding rockets as a research tool started to become obvious. Using military surplus motors kept the cost low, as did the philosophy: “Let knowledgeable people get the job done without a lot of regulations.” This provided short and efficient research programs, with valuable feedback of scientific results to the users.

The good economy of sounding rocket based research made the scientific community ask for launches of ever heavier experiments to ever higher apogees, that is longer flight/experiment time. At the same time, however, the scientific instruments became more sophisticated, and recovery of increasingly complicated and thus expensive science tools came in high demand. Recovery also paved the way for re-use after refurbishment, thereby effectively off-loading the cost of the scientific payload modules.

Land recovery is by far the easiest way to get a payload back in good shape after a suborbital flight. This however, presents new challenges:

- One must be able to predict the nominal impact point with reasonable precision in spite of varying wind conditions during launch.
- The statistical dispersion around that point must be contained inside the rocket range.

To achieve good impact point prediction, wind profile measurements were performed prior to launch, and the actual launcher settings were calculated by means of wind weighting. The statistical dispersion was lowered by increasing the length of the launcher rail, and by spinning the vehicle up to mitigate the influence of motor thrust misalignment. Even with these measures taken to their maximum performance, apogees beyond 250 km were questionable from range safety point of view at land recovery ranges.

For this reason, the S19 Boost Control System was invented in the beginning of the 1970ies. The following requirements drove its design:

- Significantly reduce impact dispersion
- Allow launch in high wind
- Stand-alone
- Reliability
- Weight
- Recoverability and re-use
- Easy handling
- Low cost

With long experience from various missile projects, the effectiveness of forward mounted canards was well known to the design team. Computer modelling, control loop analysis and simulation of rocket configurations flying through the atmosphere were routinely performed. There also was excellent knowledge in other crucial areas, such as aerodynamic analysis, rocket motor performance and analysing and modelling the elastic properties of long and slender vehicles.

The S19 system that was designed based on these requirements did indeed reduce the impact dispersion by keeping the vehicle’s attitude constant for the guidance period, in effect simulating a several kilometre long launcher rail. The guided vehicle also became 10-20 times less sensitive to wind and thrust misalignment. That meant that it could be launched under most all wind conditions. The same wind weighting procedures apply to an S19 guided vehicle, although the wind weighting parameters are different in size and sign from those of an unguided one.

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The S19 was designed as a stand-alone payload unit and did not require a lot of co-testing with the rest of the payload. The system also was designed for long term reliability, so that it could be refurbished and re-used after each mission, without having to replace expensive parts. Being part of the payload rather than the rocket motor also saved cost, since a single payload-mounted unit provides all control, regardless of the number of motor stages below. All these design features contributed to a truly low cost system.

In cooperation with NASA and SSC, the first flight ever of an S19-guided single stage Black Brant VC rocket took place at Wallops Flight Facility on 10 Jan, 1976. The flight was a perfect success, and the S19 was recovered from the Atlantic (but re-used only as a museum object, since no efforts had been made to make the unit waterproof).

The S19 was upgraded from prototype to commercial status already in 1977, and the first flight was followed by a second one in 1978 from Esrange. This time, a two stage configuration was being used with even higher wind tolerance than on the maiden flight. During subsequent years Esrange saw many guided scientific flights with apogees up to over 400 km. The upgraded system is seen in Fig 3

Figure 1. Maiden S19 flight from Wallops FF

Figure 2. Prototype S19 recovered from the Atlantic Ocean..

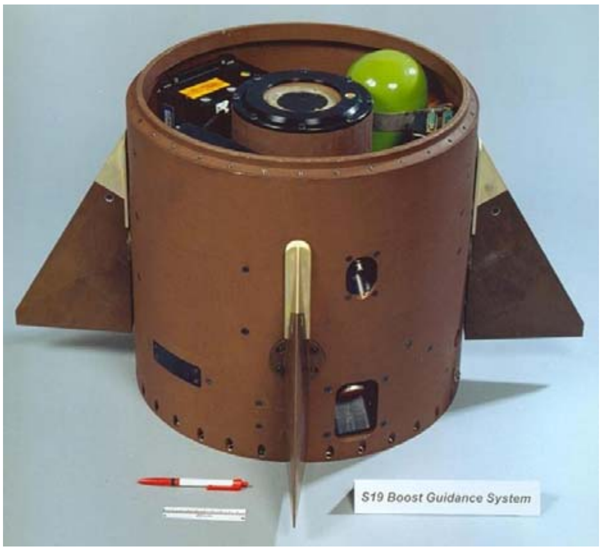

Figure 3. The operative version uses a lightweight magnesium structure and upgraded internal equipment

The analog S19 Boost Guidance System later became a money-saving cornerstone in NASAs high altitude space research flights at White Sands Missile Range, NM. A total of 185 flights were performed with the analogue S19 boost guidance systems, before they were finally retired in 2006. By then, superior alternatives had become available and used for many years.

2. ENTERING THE DIGITAL WORLD

In the late eighties, European sounding rocket based research aimed for higher apogees and long duration flights. This was driven by the upcoming construction of the International Space Station, ISS, in which research related to micro-gravity is a cornerstone. To develop experiments and to perform basic research in this field, the German Texus programme had started, but in order to get longer periods of micro-gravity, a more powerful sounding rocket platform was needed.

A goal was to achieve up to 15 minutes of high quality micro-gravity in a recoverable payload, consisting of several experiment modules. Such a long flight time of a heavy payload of course means a very high apogee and a powerful rocket motor. Recovering a heavy payload also means using a land range, in this case Esrange. To keep the impact point safely within the borderlines of Esrange, a control system for the new vehicle had to be developed. Though an S19 type canard control solution was possible, the final choice was to develop a Thrust Vector Control (TVC) system for the Castor 4B motor. The name of the new sounding rocket was Maxus.

The Guidance, Navigation and Control system for the Maxus was named GCS, and it was based upon the RIINS inertial navigation system built by Inertial Science Inc. The RIINS consisted of two parts: A despun platform with gyros and accelerometers, and a Navigation Processing Unit (NPU) that translated the output of these sensors to attitude angles & rates, as well as to position, velocity and acceleration. The third major component of the GCS was an in-house developed Guidance Processing Unit (GPU). The GPU used the navigational output signals in a guidance algorithm that provided stabilization, bending mode control and trajectory guidance for the Maxus rocket

In these early days of digital engineering, 286 and 386 processors were commonly used in home PC systems. The size and weight of the supporting electronics and their circuit boards were a lot more impressive than the capacity of these processors. For that reason, the RIINS, the NPU and the GPU pretty much filled up the volume available in the GCS unit seen in Fig 4.

In spite of some initial vehicle difficulties related to the Castor's thrust vector actuator, the GCS performed well during all launches, and micro-g experiment times above 13 minutes were achieved in a number of flights at Esrange, with apogee above 700 km.

A most important safety feature of the Maxus is that the information provided by the GCS itself is integrated into the set of Range Safety tools at Esrange. In this system, a RUAG Aerospace engineer analyses navigation and guidance diagrams as they grow in real time, and acts as an advisor to the Range Safety Officer. Flight path and gyro angles, instantaneous impact point (IIP), TVC deflections and pure status signals provide a full picture of how things are going during flight. This is a good way to make maximum use of flight safety information available.

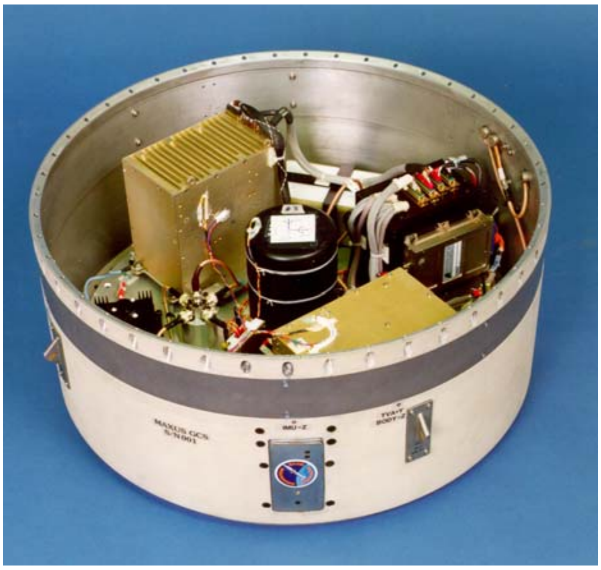

Figure 4. First generation GCS for Maxus

In parallel with the GCS, the SPINRAC and RACS systems for cold gas control of an upper stage and for payload pointing were also developed and successfully flown. These functions and their associated, flight qualified software remain available as add-ons for all RUAG Aerospace GNC systems.

3. THE S19 GOES DIGITAL…

Shortly after the first MAXUS flights, the RIINS was further refined into the much more compact and lighter DMARS inertial navigation system. The DMARS unit replaces the RIINS, the Navigation Unit and the Guidance Processing Unit. Taking advantage of the size reduction, the DMARS was made the heart of the DS19 guidance, navigation and control system, which then became a second generation S19 Family system, and the first to exhibit digital guidance&control. The DS19 is a true "fire and forget" system that flies the vehicle to a preset impact point at very high precision, and does not rely on wind weighting or accurate launcher settings.

Due to manoeuvrability restrictions at White Sands Missile Range, NM, a third generation S19 Family System was developed, with the DS19 as its starting point. It uses DS19 technology but S19 guidance strategy. Due to the close similarity to the DS19 it was named the S19D.

Figure 5. The DS19 fire-and-forget system

To reduce the control system's ability to perform rapid manoeuvres in the case of a hard-over failure, the S19D was created out of the DS19 by simply reducing the guidance time to 18 s. The S19D performs S19 type guidance, but at a much higher precision thanks to the DMARS. The S19D flight software also includes a much more efficient suppression of the vehicle's elastic oscillations, which would otherwise reduce the guidance performance.

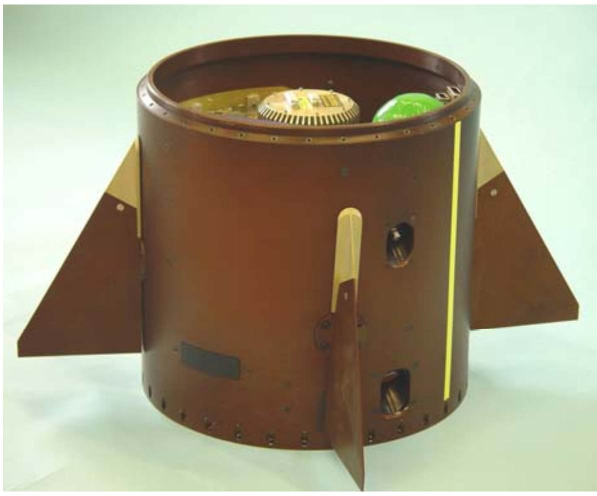

Figure 6. The S19D

As a consequence of the reduced guidance time, only one gas bottle is required. This reduces the total weight of the S19D by 1.0 kg as compared to the DS19, and by 2.9 kg as compared by the analog S19. At the same time, the impact dispersion performance has been improved by a factor of four.

4. …AND THE GCS IS IMPROVED

Once the DS19 had proven its value, a second generation Maxus GCS system was developed, based upon the DMARS. The RIINS/NPU combination worked well during all their flights, but there were reliability issues that became apparent during system testing, making the first generation GCS a bit laborious and thus costly to use. The introduction of the DMARS was a big reliability improvement for the GCS. Also, the NPU and the GPU are no longer needed, since all navigational and flight software related calculations are now performed within the upper electronics section of the DMARS.

Comparing Figs 4 and 7 shows the dramatic reduction achieved when replacing the RIINS, the Navigation Processing Unit and the Guidance Processing Unit with just the DMARS system. The redesign has reduced the total weight by more than 7 kg. The cost of the system also has been reduced, and so has the refurbishment cost, since many time-consuming tests were simplified, when the DMARS was introduced.

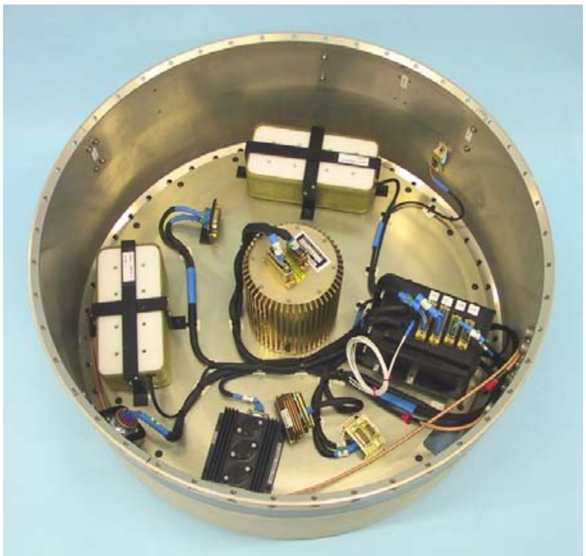

Figure 7. Second generation GCS, using DMARS

Needless to say, the second generation GCS has plenty of space available for additional apparatus. For example, RCS or ACS equipment could find a new home inside the GCS structure, and then maybe even use attitude data from the DMARS for control purposes.

5. S19L, THE FOURTH GENERATION

Although the S19D has fulfilled its guidance and control tasks flawlessly in its 13 launches to date, technological development has allowed for a fourth generation member of the S19 Family of Guidance Systems to be born, the S19L. This system is centred on the LN200 Inertial Measurement Unit. In contrast to the DMARS with its despun platform, the LN200 is a strap-down system. Its accuracy and sensing frequencies are high enough to provide sufficient stability margins in the vehicle control loop and to resolve all canard commands correctly during the guidance phase of the fast rolling rocket.

In addition to performing the required boost guidance during 18 s, the S19L also provides navigational data such as position, velocity and Instantaneous Impact Point (IIP) information, using acceleration data from a package of accelerometers housed in the LN200. The use of solid state sensors (as opposed to a spin-stabilized inertial navigation unit with mechanical gyros) has reduced the complexity of the S19L and thus, improved the over-all reliability of the system. With impact dispersion performance just barely below that of the S19D, the S19L has the advantages of lower weight and power consumption, easier handling, better system overview and last but not least, lower price. The weight of the S19L is 4.5 kg below that of the S19.

Fig 8 shows two S19L units, both of which are actually converted S19 systems that re-use the main structure, the pneumatic system and some additional parts. The LN200 is located in the centre of the module, but due to its small size, it is hardly visible. Its output is conditioned and used by a small two circuit board Guidance Processing Unit (GPU) developed by RUAG Aerospace and DST Control of Linköping, Sweden. The time for system self-alignment is 2 min, as compared to 7 min for the S19D. This feature further streamlines the countdown procedure.

Figure 8. The S19L

6. COMMON FEATURES

RUAG Aerospace guidance, navigation and control systems provide the following major advantages:

- Significantly improved impact dispersion performance, as compared to unguided vehicles, allows for high apogee / long duration flights at geographically limited rocket ranges.
- High wind tolerance provide highly relaxed launch conditions, and the rocket can be launched when the scientist wants to, not when the weather situation so dictates. Typically, a Terrier-BBVC vehicle guided by the S19L can be safely launched into a wind profile of 10-15 m/s at ground level, increasing to 50 m/s at 10 km of altitude. The wind limits of the GCS guided Maxus are similarly high.
- Recent systems provide an excellent single-screen overview of a multitude of system status and ready-to-launch data during countdown and flight.
- Situational awareness data for Range Safety, including heading, position and velocity data as well as in-flight instantaneous impact point prediction.
- Navigational and pointing data for scientists and other users, for use on-line or during post flight data reduction exercises.
- Recent systems also are lighter and more reliable than the early versions, and close-to-outdated technology has been replaced with currently available hardware.
- System interfaces have become more standardized, such as RS232 and RS422 data interfaces.
- Minimum battery capacity is 20 minutes. This means that navigational and attitude data remain available not only during guidance, but throughout the flight.
- Finally, the cost of the newer systems is lower thanks to less complicated solutions. The same holds true for their refurbishment cost.

7. FUTURE SYSTEMS

The trend towards more capable guidance, navigation and control systems is likely to continue, following the general improvements of worldwide technology. Also, to remain available, future systems must be upgraded with up to date technology.

Can the systems be made lighter and smaller? Not a whole lot, since the size and weight of the actuators reflect the size and weight of the sounding rocket they control. The actuators and their supporting components then dictate the size and weight of the outer structure. Minor reductions remain possible though, thanks to the on-going miniaturization of electronics and battery cells.

Looking at the whole payload, size and weight reductions are possible by integrating more functions into the guidance modules, such as telemetry and/or recovery system electronics.

Also, by adding a low-cost cold gas module to any of the RUAG Aerospace guidance systems, the performance could include RCS, ACS and/or upper stage trajectory control capabilities. The cold gas module would only contain a gas supply, thruster valves and interface electronics. The guidance system's inertial navigation sensor and additional RCS/ACS software resident in its guidance processing unit would provide commands for the thruster valves.

8. FUTURE APPLICATIONS

Guidance, navigation and control systems improve the flight time, the on-time launch probability and the impact dispersion of sounding rockets. With a guidance system onboard, the rocket is normally launched on the first day regardless of the wind situation, reducing range and personnel costs already in current applications. The following applications or research areas are likely to benefit from the additional flight time offered by guidance and control systems:

- In-flight verification of experiment modules later to be launched on satellite missions, as well as calibration of experiments that already fly on satellites.
- Astrophysics missions, where a telescope is pointed at an object of interest for as long a time as possible.
- Extremely high apogee missions, in which an upper exo-atmospheric stage is stabilized after atmospheric exit, re-pointed and kept stable during motor burn. Apogees over 1000 km are quite possible, using already flight proven SPINRAC software as an add-on to the RUAG Aerospace guidance systems.
- Tailored trajectories, again made possible by the re-pointing of an upper stage prior to ignition. Such trajectories can be useful for scramjet and other re-entry experiments, as well as for target missions in missile defence type applications.

Some rocket ranges, such as the Australian Woomera rocket range and ranges that utilise vast oceanic areas for impact are currently considered large enough to allow for unguided launches. This situation may change for the following reasons:

- Very high apogee, long duration flights may render even these large impact areas too small.
- Extremely large impact areas cannot be completely cleared from people or valuable objects during a launch. The risk of damage to humans living in or travelling through very large impact areas during launch is not negligible. Boat and airplane traffic through oceanic ranges serve as examples.
- Recovery in a remote oceanic area is very difficult, when the recovery vessels have to cover the vast search areas associated with unguided, high apogee flight.

The solution to the above problems spells guidance, navigation and control.

9. CONCLUSION

An on-going development and refinement of multiple generations of guidance, navigation and control systems has been described. Trends of higher capacity, easier handling, better system overview, lower weight and lower cost have been demonstrated. The quality of on-board situational awareness data for Range Safety support and of attitude data for science support also has been greatly improved over the years.

The further development of new guidance system generations is driven by technological achievements as well as by requirements of new applications, especially those that are associated with extremely high apogees and tailored trajectories.