TRW's T310 SPACECRAFT BUS, A STABLE ALTERNATIVE FOR BROADBAND SPOTBEAM

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ABSTRACT

Modern broadband satellite communications systems rely on small spot beams requiring precision pointing to optimize system performance. TRW's lightweight T310 spacecraft bus, the first in a series composite spacecraft product lines, is ideally suited for communication satellite systems requiring an ultra-stable pointing platform—proven on the GeoLITE mission launched in May 2001.

The T310 bus has demonstrated its capability to autonomously meet the stringent pointing performance required by spot beam communication payloads without relying upon a complex RF autotracking system. The T310 bus achieves excellent pointing control through the use of a thermally stable composite core structure and a high performance attitude control system (ACS).

Its compact structure allows it to be launched in a 3-m diameter fairing; and it can easily be adapted for larger fairing sizes to accommodate bigger payloads. This paper presents, and compares against industry alternatives, unique pointing capabilities of the flight-proven T310 spacecraft bus necessary to meet the demanding requirements of future broadband communication payloads.

INTRODUCTION

T310 is a 3-m-class spacecraft—compatible with fairings 3-m and larger. The first T310 spacecraft was manufactured for NRO's GeoLITE program, successfully launched in May 2001.

The primary purpose of any spacecraft bus is payload accommodation. Critical functions include providing power control, structural support, temperature control, stationkeeping, pointing stability, and command and telemetry trafficking. Geosynchronous satellites are traditionally measured on the amount of payload mass and power they can accommodate; although, available payload mass and power depend on constraints such as on-orbit life and launch vehicle options. In addition, all theses payload support functions have to be performed reliably throughout the life of the satellite.

For high bandwidth narrow spot beam applications such as Ka Band frequencies and higher, the ability of the spacecraft bus to provide stable antenna pointing becomes of increased importance. TRW's T310 spacecraft is well suited to meet these stringent pointing requirements. They are flowed to the spacecraft from a system-level pointing budget. To achieve an economical and reliable antenna pointing solution, error sources are budgeted to both the bus and payload. Different approaches to pointing improvements are then evaluated. There are many approaches, discussed below, that can be used to improve pointing accuracy.

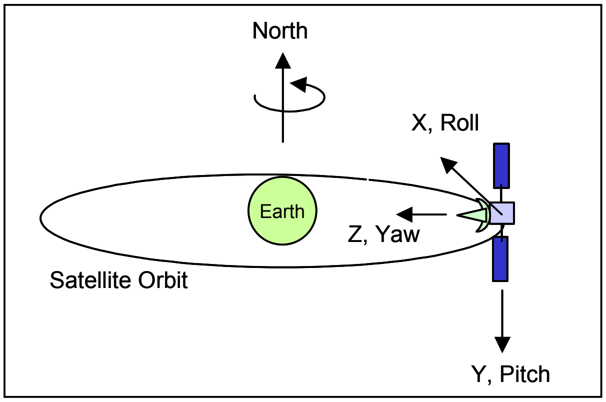
Satellite Pointing Budget

A pointing budget shows how the individual bus and payload errors are itemized and summed into an overall system error in each of the three spacecraft axis and for various time periods (shown in Table 1). The total error is the antenna boresight pointing error. Typical error budget may have hundreds of line items for both the bus and the payload. The budget discriminates errors in four temporal categories: fixed, seasonal, diurnal and short-term errors. Each error entry is decomposed into the spacecraft orthogonal axes: roll, pitch and yaw (shown in Figure 1). All errors within each temporal are typically Root Sum Squared (RSS) together due to their independent nature. The most conservative approach is to algebraically-sum the four temporal values together. This can be considered pessimistic because it is based on the unrealistic assumption that each component contributes it's worst-case pointing at the same instant in time. Fortunately, many customers permit the use of the more realistic RSS method.

Table 1. Satellite Pointing Budgets for Star Tracker Based and Earth Sensor Based Systems

	A. STAR TRACKER-BASED			B. EARTH SENSOR-BASED		
	Spacecraft Coordinate			Spacecraft Coordinate		
Error Source	Roll	Pitch	Yaw	Roll	Pitch	Yaw
Fixed/Long-Term	0.012	0.012	0.012	0.012	0.012	0.012
Seasonal	0.010	0.010	0.010	0.012	0.012	0.012
Diurnal	0.017	0.017	0.024	0.037	0.037	0.060
Short-Term	0.013	0.013	0.024	0.050	0.050	0.070
System Total	**0.052**	**0.052**	**0.070**	**0.111**	**0.111**	**0.154**

Figure 1. Satellite Coordinate Definition



Often times, on-orbit operations are used to reduce fixed alignment errors between the spacecraft's attitude reference and the antenna boresight. When there are multiple antenna apertures, misalignment often cannot be correctly completely—some compensation to all apertures may be attained by rotating the satellite a fixed amount about the Z (yaw) axis.

Finally, a budget typically distinguishes pointing error between normal and maneuver modes. During spacecraft maneuvers, which is when the thruster turns on and off, the transient can increase the bus short-term errors, especially when chemical thrusters are used. The duration of this increased error is very short, say <5% of orbit time, so it is categorized as maneuver mode error budget. The quiescent spacecraft duration, which is the majority of on-orbit time, is categorized as normal mode. The distinction between the two modes is useful in link availability analysis. The marginally higher pointing error during maneuver mode can reduce service availability.

Satellite Pointing Options

So far, the pointing requirements of current generation broad beam L/C/Ku-band communication payloads do not exceeded the pointing performance of spacecraft buses using earth/sun sensors for attitude reference. As more advanced systems are fielded using spot beam and laser communication payloads, much better attitude reference sensors become necessary. The use of traditional earth/sun sensors is inadequate to support the higher power and mass demands of these broadband missions and would result in the degradation of service.

Table 2 shows available pointing options. Earth/sun sensors are the baseline on many commercial spacecraft. Adding RF sensors marginally improves bus pointing, while using star trackers significantly improves bus pointing. The payload has options to improve pointing as well. However, other operational constraints and complexities limit the choice of payload pointing.

Table 2. Satellite Pointing Options

Bus Pointing Options		Payload Pointing Options	
Star trackers	Best	Autotrack	Best
RF sensor	Better	Open-loop	Better
Earth/sun sensors	Worst	No-gimbal	Worst

For example, autotracking a multibeam antenna requires beacons either inside or outside the user beams. Beacons inside the user signal increase complexity, mass, and power to the payload while beacons outside the user beams add complexity and cost to the ground segment.

Accommodating payloads requiring less than 0.10 deg of system pointing is very challenging, if not impossible, without using star trackers for attitude reference. Shown previously in Table 1 was a comparison of two satellite-pointing budgets, one based on star tracker and the other on earth/sun sensor. (Payload errors are ignored for illustration purposes and vary by mission.) Using star trackers result in a significant reduction to the total system error.

Comparison of Pointing Options

Few technology advances offer comparable cost savings as the stellar inertial-based system of the T310 ACS. It typically isn't needed for broadbeam payloads, but is an enabler for payloads requiring fine pointing, such as narrowbeam communication payload like those proposed for Ka Band systems. Table 3 summarizes the three common pointing schemes. The advantages and disadvantage are discussed below.

Other than the initial investment of bus development, recurring cost of producing a star tracker-based spacecraft is the same as that for earth/sun sensor-based spacecraft, although there are no significant impacts to the overall spacecraft mass and power for either type of sensor. The life cycle cost for operating a star tracker satellite can be less than an earth/sun sensor-based satellite because it does not require frequent ground contact and calibration. The significant cost is in the bus hardware and software developments, of which TRW has already completed for the baseline T310.

In RF autotrack pointing systems, the autotrack beacon signals are received through payload antenna apertures and processed by an RF receiver. The spacecraft onboard computer processes data from the RF receiver and converts it to a signal that the gimbal drive electronics can use to drive the antenna gimbal.

Compared to star trackers system, antenna autotracking systems are more expensive and complicated; using ground beacons that cross multiple bus and payload interfaces. Ground beacons are

Table 3. Advantages and Disadvantages of Star Tracker, Autotrack, and Earth Sensor

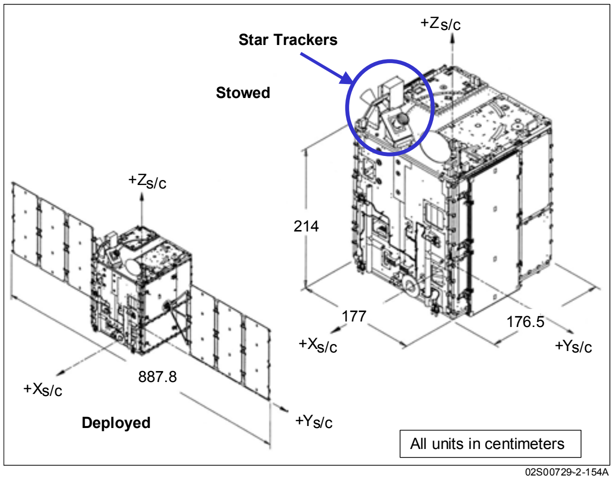
	Star Tracker	Autotrack	Earth Sensor
Recurring cost per satellite	<$1M	>$5M	<$1M
Pointing knowledge	0.001 deg	0.01 deg	0.01 deg
Bus pointing accuracy at antenna interface	0.01/0.01 deg roll/ pitch, 0.02 deg yaw, 3σ	N/A	0.1/0.1/0.2 deg, 3σ
Pitch/roll/yaw attitude knowledge	Yes/Yes/Yes	Yes/Yes/No	Yes/Yes/No
Yaw error variation	No	Yes, when tracking beacons are close together	NA
Flexibility of satellite relocation	Yes	No, ground beacons not in view, may require repositioning earth sensor	No, may require repositioning earth sensor
Ground–satellite interface	No	No	Update satellite earth radiance data, sun/moon avoidance planning
Mass impact	5–10 lb/star tracker	~100 lb for autotrack hardware, RF receiver, gimbal, gimbal drive electronics, etc.	5–10 lb/earth sensor
Power impact	10 W	50-100 W plus 10 W for attitude sensor	10 W plus any additional payload power to make up for oversized beam
Field-of-view	30 deg from North/South axis of ecliptic plane	Earth	Earth

implemented either inside or outside the user beams. If they are inside the user beam, the beacon frequency and guard bands occupy precious frequency spectrum allocated to the user. Furthermore, the payload architecture is more complex requiring higher payload mass and power. Likewise, if the beacons are outside the user beams system cost and complexity are increased because additional ground assets are required.

An autotrack system can be further detrimental to space vehicle cost. The increased mass and complexity impacts satellite dry mass and, therefore, orbit maintenance propellant, transfer orbit propellant, and launch vehicle sizing. It also impacts the ground segment, for example, additional ground sites for beacon sources are needed for each antenna aperture. In addition, beacons are impractical in military applications, because they are susceptible to jamming.

TRW has extraordinary experience flying star tracker-based satellites and building thermally stable spacecraft platforms. The T310 is one of TRW's "T" series-family of composite spacecraft platforms designed for missions requiring an extremely stable, low-jitter platform with precision pointing and optical bench capability. The key to precision pointing is in the spacecraft advanced ACS and structure design. The advanced ACS achieves a pointing accuracy of 0.01 deg about roll and pitch, 0.02 deg about yaw axis, 3σ, resulting in antenna pointing in an order of magnitude better than the current generation of commercial GEO buses. This achievement is a result of using star trackers as an attitude reference sensor and an extremely stable graphite composite structure. Figure 2 shows the placement of two star trackers off-pointed from the North/South axis of ecliptic plane. Unlike an earth sensor that can only provide roll and pitch attitude, star trackers can resolve attitude data in all three axes.

Figure 2. T310 Bus Configurations



The importance of precision pointing is most visible in the multiple spot beam payloads where better pointing improves C/I, EIRP, SFD and G/T; thus giving better payload performance and lower payload DC power. This reduction in power is of substantial benefit because the payload is one of the largest consumers of mass and power on the spacecraft. The benefits don't end here. Lower electrical power means less thermal dissipation is required. All these benefits mean lower satellite dry mass, which means less propellant for orbit maintenance, less propellant for transfer orbit, and lower satellite wet mass. This savings can lead to potential customer benefits such as an increase in payload content or use of a smaller (cheaper) class of launch vehicle.

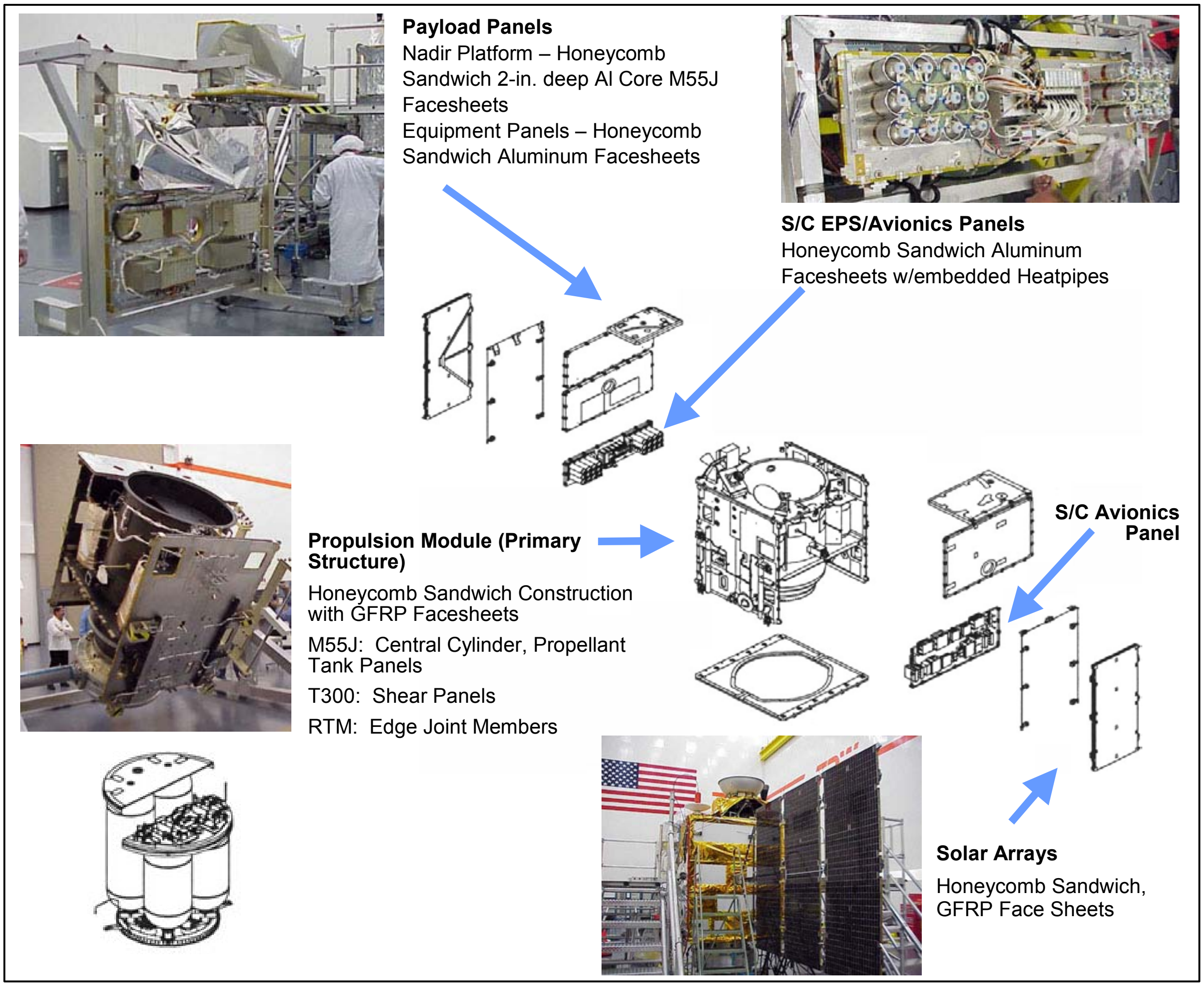
The advantage of using star trackers goes beyond pointing accuracy. It offers more autonomous operations for both payload and spacecraft. For example, to minimize errors earth sensors typically require a periodic ground interface to update earth radiance and sun and moon intrusions. Conversely, star tracker FOVs are North/South of the ecliptic plane, not the earth; thereby, not likely to compete with payload and bus antennae for earth FOV. Unlike the traditional earth sensor location at the valuable nadir end of the spacecraft, star trackers can be located closer to the antenna interface.

Other features of the T310 ACS design allow a communication payload to take full advantage of its precision pointing. The zero momentum system, compared to a pitch momentum bias used on some other buses, allow the satellite to off-point from nadir continuously. This is useful for changing the service region due to market demand or for contingency planning. Another T310 feature is the ability to fly upside down (180-deg yaw flip). This maneuver was executed flawlessly in-orbit on the GeoLITE mission. This maneuver gives yet another dimension of flexibility for responding to changes in communication services.

T310 Spacecraft Structure

To achieve spacecraft pointing performance, the T310 structure was designed to maintain dimensional stability. Figure 3 shows major components of the structure. The spacecraft's primary load-carrying

Figure 3. Exploded View of T310 Structure Elements



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structure consists of a graphite composite central cylinder to which the nadir payload platform and North/South panels (aluminum honeycomb core, graphite face sheet) are attached using titanium flexures. This design provides a rigid and extremely thermally stable structure that is ideal for hosting spot beam and laser communication payloads. Another advantage of the structure is it can fit in a 3-m fairing launch vehicle. Although, launching in a more commonly available 4-m fairing can be done and allows more space for larger/more antennae.

The T310 design is modular and versatile to support short program schedules. The spacecraft central cylinder supports payload panels, spacecraft bus equipment panels, and the propulsion module. The design allows for parallel integration and test of both bus and payload equipment.

T310 Capabilities and Production Schedule

Table 4 summarizes the payload performance capability of the T310. The spacecraft can provide nominal payload DC power up to 1600 W, 22–38.6 Vdc. The payload mass capability can vary and depends on the mission and class of launch vehicle. As described in this paper, the spacecraft can perform precision antenna pointing to 0.01 deg about roll and pitch and 0.02 deg about yaw axis.

Table 4. T310's Payload Accommodation Features

Spacecraft Characteristics	
Payload power capability	1600 W
Payload mass capability	Depends on launch vehicle
Pointing control accuracy roll/pitch/yaw, 3σ	0.01/0.01/ 0.02 deg
Design life	15 years
Data bus	1553

On a recurring basis, a completed spacecraft bus can be delivered in 17 months—easily supporting a typical commercial program schedule. TRW delivered the first T310-based satellite, GeoLITE, in 40 months, which included bus and payload development work. Figure 4 shows the baseline T310 production schedule.

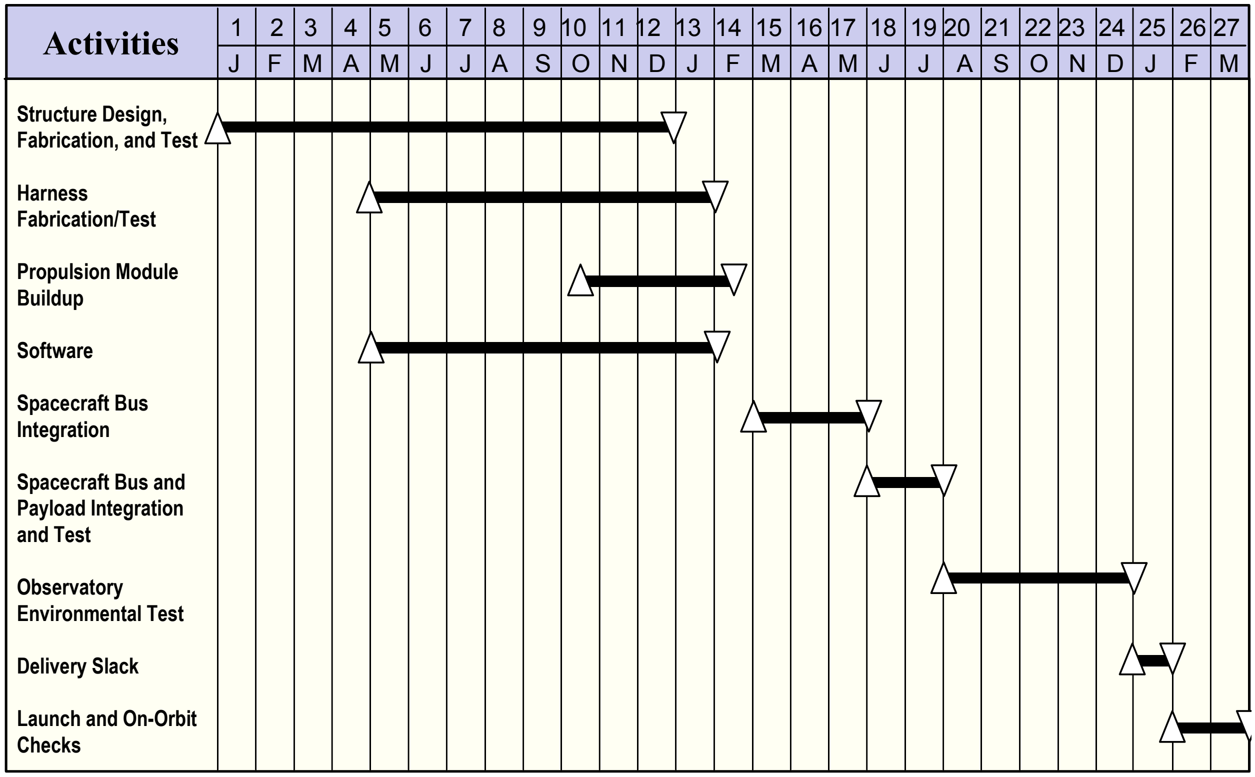
SUMMARY

TRW's has developed the T310 spacecraft product line using heritage hardware and software with a record of flawless on-orbit performance. The use of state-of-the art stellar inertial sensors and composite structure gives the T310 bus the capability to accommodate the stringent pointing requirements of advanced spot beam and laser communication payloads.

ACKNOWLEDGEMENT

Thanks to the entire T310 team for their help in this paper. The on-orbit success of GeoLITE is the proof of the T310 capabilities.

Figure 4. T310 Satellite Production Schedule



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