Tracking and operations of Constellation microspacecraft

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The Magnetospheric Constellation mission involves tracking and operations of a large number of satellites; a challenging task even for identical spacecraft, if costs are to be kept at bay. A "store and dump" policy dictated by power savings considerations is a necessary but not sufficient condition for inexpensive operations. We present the elements of a simple, robust and cost effective tracking and operations system that can be used by a few to a few tens of satellites. As a case-in-point we use the proposed Constellation pathfinder mission QUATRO to demonstrate the telemetry subsystem, satellite acquisition, launch and early orbit operations, routine tracking and science operations for the less daunting situation of four autonomous spacecraft. Commercial-off-the-shelf telemetry and ground systems components are employed. Backing up our results with experience gained from the SMEX program we show how such technologies and ground systems can handsomely handle the tracking and operations of many tens of identical autonomous microsatellites.

1. INTRODUCTION

The Magnetospheric Constellation mission consists of a large number of identical microspacecraft, equipped with simple instrumentation, which when viewed as a whole they provide a unique and much needed view of magnetospheric processes. In particular, the Constellation microsatellites if populous enough, can differentiate between spatial and temporal evolution, can evaluate the growth and decay of free energy within spatial gradients extended over wide regions and can track the propagation of energy and information throughout the magnetosphere.

Providing a generic solution for Constellation class missions may be discouragingly costly and unsettling. A stepwise Constellation deployment is a scientifically lucrative approach that may benefit the tracking and operations development as well [Angelopoulos and Spence, 1998]. This approach, originally proposed by Siscoe [1998], calls for a series of self-justified, well-focused missions each one building on the experience of its predecessor.

We have proposed a low-cost Constellation pathfinder, the QUATRO mission [Delory et al., 1998], that can provide much needed information pertaining to magnetospheric energy releases. Its findings can aid orbit planning and validate technical aspects of a more populous magnetospheric multiprobe armada. The mission entails four identical spacecraft that will be placed to a Geosynchronous Transfer Orbit (GTO) as a piggyback package on a launch vehicle that has 100 kg of available throw-weight. The spacecraft will then use their own, identical propulsion systems to raise altitude to 12 Re and move to a near-equatorial orbit. Delory et al. [1998] described the mission's scientific objectives, the spacecraft mechanical and electrical subsystems, the low cost propulsion system that enables orbit and attitude control, and the well studied piggyback ride and release. In the present paper we describe issues that pertain to tracking and operations for Constellation mission microspacecraft, again by using our proposed mission as an example.

On QUATRO, just like on Constellation, the on-board and ground telemetry system requirements are scaled by the data transfer rate of science quantities. A store-and-dump policy for data retrieval is necessary. Otherwise, tracking near apogee, i.e., the most interesting part of the orbit, would result in inordinately low data rates unless unacceptably high on-board power, or costly Deep Space Network antennas were employed. Conversely, a 2 Watt transmitter at a typical 10% efficiency, can operate during a single, 10min tracking session every one 12 hr-orbit, requiring approximately a 0.3 Watt orbit average power. Assuming recharging operation takes places during a 3 hour period, a 2 Watt charging power is more than adequate for data transmission and is commensurate with the power requirements of the other subsystems. Using a 10m diameter ground antenna we can achieve 200kbps rates from a 20000 km range source, at adequate link margin. In 10 minutes we can thus download 120 Mbits which becomes our target data collection per orbit.

Using this back-of-the-envelope calculation as a guide, we proceed to show in Section 2 that the low data accumulation and transmission rates employed result in significant scientific information. We explain how the data will be collected and processed on-board., and discuss the need for on-board data retention and prioretization of orbits in anticipation of limited tracking sessions. In Section 3 we describe the requirements that the spacecraft ascent to the final orbit places on mission control and operations. We then detail, in Section 4, the appropriate spacecraft and ground RF systems that are commensurate with low cost operations, and derive the associated link margin. Section 5 deals with the spacecraft attitude and orbit determination system and associated operations. Section 6 describes a science and mission operations center derived from the experience of FAST and HESSI missions. The center incorporates spacecraft integration and testing resulting in significant pre-launch cost-savings. In Section 7 we carry over the lessons learned from QUATRO to a Constellation of 60 equatorial spacecraft and show how the tracking and operations component of such a mission can benefit from practises learned from the SMEX program, i.e., from low-cost, robust COTS technologies and efficient, flight-proven, low-risk automation.

2. DATA COLLECTION AND PROCESSING

A magnetometer, a plasma ion and electron spectrometer and two, 36^o field of view, energetic ion and electron telescopes are the instruments on board QUATRO. Magnetometer data are collected at 16 vectors per spin at all times. Plasma moments are computed and stored for every spin, while full distribution functions (FDFs) for data validation are stored at a lower time rate (once every 20 spins, i.e., 40 s). Reduced distribution functions (RDFs) employing energy- or angle- averaging or FDFs are stored during burst mode operation at a full time resolution. Despite the low data accumulation on each spacecraft (Figure 1), scientifically invaluable information is obtained from the mission since the novelty in the approach of multi-point sampling of the magnetosphere

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lies in the number of spacecraft and their optimum locations.

QUATRO SCIENCE DATA ACCUMULATION

	PLANNED INSTRUMENT DATA RATES	
ESA Ions or Electrons	Full Distr. (88 angles, 16 energies) (FDF): 11264 bpSpin	Reduced Dist. Functions (RDF): Energy/angle: 3500 bpSpin Gyrophase (e- only): 1024 bpSpin
SST Ions or Electrons	Full spectra: (2 elev., 16energies) 1792 bpSpin	
MAG	Full (16 vectors/spin) 768 bpSpin	

ROUTINE DATA ACCUMUMATION

ESA:	Ion and Electron moments every spin	192 bpSpin
	One Ion FDF (Ave. or Inst.) and	
	One Electron FDF per 20 spins	614 bpSpin
SST:	Total counts from the detectors/both SSTs	48 bpSpin
	Full energy and angular res. per 20 spins	180 bpSpin
MAG:	16 vectors per spin	768 bpSpin
TOTAL		1802 bpSpin

BURST DATA ACCUMULATION

ESA:	One FDF every 4 spins	2816 bpSpin
	Three RDFs every 4 spins	2816 bpSpin
	Electron PADFs	1024 bpSpin
SST:	Full E, Channel and Sector every spin	3584 bpSpin
MAG:	16v/s	768 bpSpin
TOTAL		11008 bpSpin

QUATRO ORBIT SUMMARY

Spin Period(SP) = 2 s
Orbital Period (OP) = 24 hours
Routine Accumulation Interval (RAI) = 18 hours
Burst Accumulation Interval (BAI) = 3 hours
TOTAL = 1802*RAI/2s + 11008*BAI/2s = 118 Mbits

Figure1. Data accumulation rates and orbit summary for the QUATRO spacecraft, or a typical Constellation probe.

The data collected from the three instruments are processed on a single data processing unit (DPU) composed of two 3”X6” boards. Elimination of instrument-specific processor boards is possible on such microspacecraft if steps are taken to minimize high speed computations and complex operations. A single 8085 processor with two Actels can achieve the computational requirements of QUATRO. Board real-estate is further minimized by surface mount architecture, and taking advantage of high density space-qualified memory packs. Additionally, this approach eliminates multiple connectors, boxes and interface agreements between experiments and DPU, and it simplifies integration and testing.

The electronics schematic of the spacecraft is shown in Figure 2. Plasma data collection is keyed on the sun pulse via a spin phase sector clock generator. The magnetometer zero-crossings are used to provide an estimated field direction during a spin, used to reduce full electron distributions to two dimensional, pitch angle ones. An on-board trigger which is being used successfully on the WIND spacecraft looks for sharp magnetic field or plasma flow changes and records the previous 10 minutes and the ensuing 50 minutes on burst mode memory. All data are encoded and compressed using the Rice compression scheme. The data collected from a single orbit are then stored for downlink during the next available tracking opportunity. Convolutional encoding/decoding further reduces the bit-error over noise ratio.

A single ground antenna can download 55% of the data from any QUATRO satellite. On the other hand, we are primarily interested in data when all probes collect useful data at the magnetosphere. Thus, at a given contact opportunity, not the current orbit’s but a previous orbit’s data that has not had an opportunity to be downlinked may be more useful to receive. It is straightforward to design an orbit prioretization scheme once the mission orbital elements have been definitively established. However, provision should be taken that an orbit’s data be kept on solid state memory for several orbits increasing memory capacity and retention requirements. Luckily, S-RAM memory at 10Mbytes per chip has been flight-proven on FAST, and has the high density and data retention required for the mission.

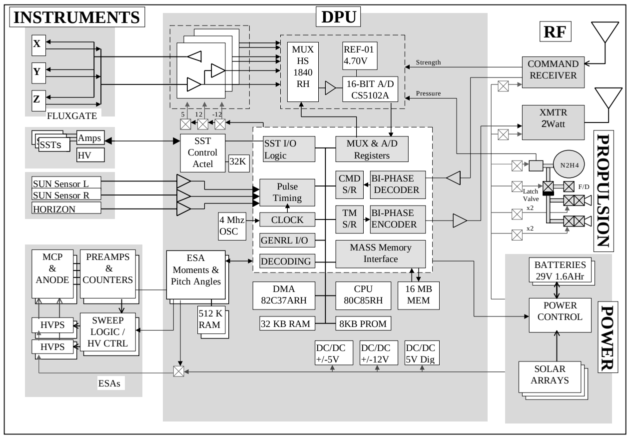

Figure2. Logical diagram of subcomponent relationships of the QUATRO electronics. The simplicity of instruments, the low level of required computations and the simple spacecraft control operations permit all spacecraft functions to be performed with an 8085 processor and two Actels.

3. LAUNCH AND EARLY ORBIT OPERATIONS

A significant component of the QUATRO mission is the ascent to the final orbit via a series of low thrust maneuvers. Inadvertent small errors during the pre-planned maneuvers can be corrected by adjusting the following ones, without the need for continuous real time spacecraft monitoring and adjustments because of the selection of low impulse thrusters. The launch represents a generalized, inexpensive method to reach altitudes beyond GTO. The requirements placed on tracking and operations are outlined below.

The Centaur upper stage performs release of the primary spacecraft at point GSEP, an event tracked by station Ascension Island (Figure 3) and then performs a main spacecraft avoidance maneuver. It spins up towards the QUATRO release attitude, in order to settle the remaining fuel, and then it releases and spins up the four microspacecraft at QSEP. The event is within the field of view of Diego Garcia, a station routinely available for communications with the upper stage of the launch of the Atlas launch vehicle. The positive separation signal of the QUATRO spacecraft by the Centaur upper stage is naturally monitored. The Centaur/QUATRO definitive orbital elements upon release will be recorded by NORAD using C-band radars or optical means and be reported to the missions operation center. After a QUATRO collision and contamination avoidance maneuver Centaur depletes all remaining fuel and becomes a passive object.

QUATRO is passive throughout launch and release, its battery trickle charged at the launch pad, and withstanding 30 days or more of charge retention. Its computer turns on with a timer after switches with the desired built-in redundancy signify occurrence of the release. QUATRO is released spinning at 30 RPM with spin axis normal to the ecliptic, allowing immediate battery recharge. The spacecraft receiver then turns on at a strobe mode and awaits commanding from the mission operations center. Electromagnetic interference compatibility requirements are fulfilled for the mission studied.

Test fire and in-orbit final characterization of the thrusters, reorientation for verification of dynamic stability, and ACS checkout take place immediately after spacecraft acquisition. All these operations require the ability to track the spacecraft at any point in the orbit at any given time. Since the GTO orbit is high enough, two anti-diametrically located stations are adequate for nearly continuous orbit monitoring. Exception to this rule are perigee contacts which are short, infrequent and with limited field of view and if desired they must be scheduled well in advance.

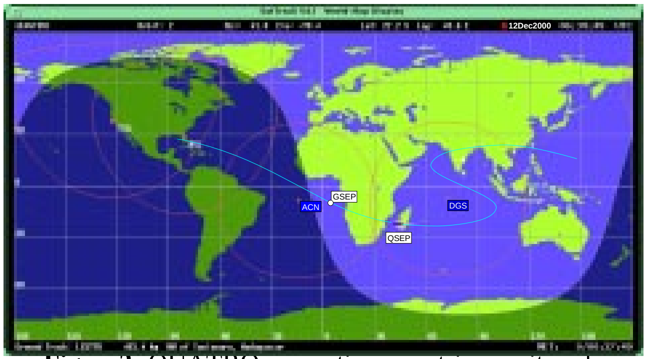

Figure3. QUATRO separation event is monitored as a part of routine launch vehicle upper stage operations.

Following release, ascent to the final orbit begins. The propulsion system behavior (Figure 4, left) has been characterized using laboratory calibration data and in-orbit performance data from previous flights of the thruster model used. The sequence of thrusts is composed of an apogee fire for initial perigee raise, 9 perigee fires for apogee raise, and 4 apogee fires for inclination change.

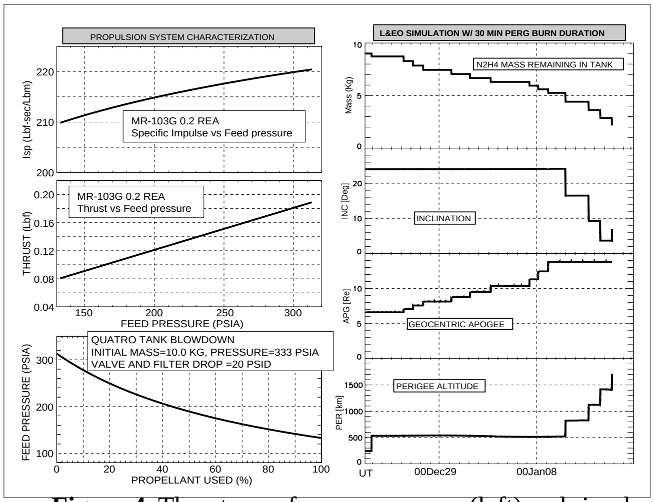

Figure 4. Thruster performance curves (left) and simulation of the ascent from GTO to final 1500 km perigee altitude by 13 Re apogee geocentric distance (right). The simulation (right) has been ran using two ground stations (UCB and DGS, see text) and realistic thruster and spacecraft parameters. The orbit integrator is GTDS (see Delory et al., [1998])

All maneuvers are planned to take place when adequate station coverage of the event from one of two available ground stations is possible. Ground stations UCBerkeley (UCB; an 11 m NASA station) and Diego Garcia (a 10 m AFSCN station in the Indian Ocean) are used as working examples. In the realistic parameter simulation of the ascent sequence (Figure 4, right) the final orbit is attained by one spacecraft within 28 days. A shorter ascent duration can be achieved with longer thrusting at each contact opportunity incurring a penalty on fuel utilization efficiency.

The resulting orbit is shown in Figure 5. Each QUATRO spacecraft is typically following the other in contacting the same ground station such that all four spacecraft will undergo the same orbit adjustment from a few minutes to one orbit later. Thus, all spacecraft are separated in their ascent by less than four orbits (4 days maximum); the total ascent duration will be 32 days maximum.

Ground station near-continuous coverage through L&EO operations is crucial for mission survival. Additional stations used for backup are Wallops Island (WAL; a 10 m antenna) and Madrid (RIT; part of the Deep Space Network). The first few orbit passes and the evident near-continuous station coverage by both primary and backup stations is shown in Figure 6.

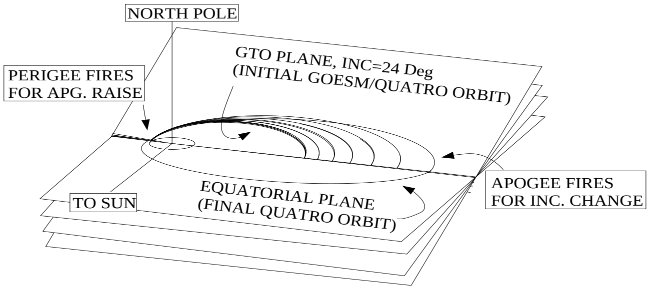

Figure 5. Orbit evolution of the run of Figure 4 (right).

When the apogee of the initial, GTO orbit is pointing towards dawn or dusk (as in fact is the case in the specific launch studied), then the spin orientation required for perigee and apogee raise fires is roughly along the sun direction. This situation leads to decreased power input through the solar panels. Resolution calls for a reorientation to the fire direction prior to each main deltaV maneuver and a reorientation back to the power-favorable direction after the main deltaV maneuver. A 90 degree rotation of the spacecraft, in the pre- and post- orbit-maneuver-fire can be accomplished within less than 10 minutes by pulsing the main thruster once per three spins, for 90 degrees of spin phase each time. Verification of the control sequence comes from GMAN, the Generalized Maneuver program, routinely utilized by GSFC and currently operational at UC Berkeley. Contact with a ground station is maintained through all reorientation maneuvers as shown in Table 1.

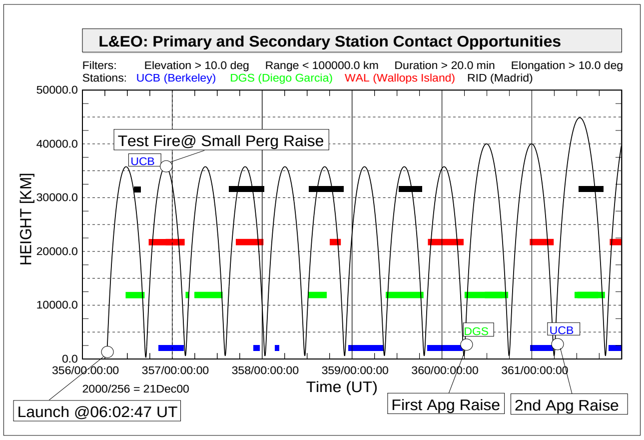

Figure 6. Tracking QUATRO during the first 12 orbits.

Any reorientation maneuver at perigee (Figure 7) results in gain loss due to deliberate mispointing, which is counterbalanced by a decrease in range below the nominal 20,000 km. The deliberate mispointing is due to our choice of a reorientation maneuver along a major-circle. Dog-leg maneuvers (i.e., performed in two or more steps which avoid high gain losses) are an alternative solution. The lesson learned, however, is that since spacecraft reorientations affect the link margin, is important to have near-real time monitoring of the spacecraft during these otherwise pre-planned events. This can ensure the agreement of the on board attitude data with the model behavior during reorientations and can signal early termination of a sequence in the event of inadvertent divergence from model behavior.

CONTACT ID	GROUND STATION	UT-BEGIN CONTACT AND PRE-DV REOR (YYMMMDD/ HH:MM)	DURATION [min]	UT-BEGIN DV MANEUVER (YYMMMDD/ HH:MM)	DURATION [min]	CONTACT ID	GROUND STATION	UT-BEGIN CONTACT AND POST-DV REOR (YYMMMDD/ HH:MM)	DURATION [min]
01A	UCB	01Mar21/21:55	10	01Mar21/22:05	12	01B	UCB	01Mar21/22:21	10
02A	UCB	01Mar25/05:33	10	01Mar25/05:43	20	02B	DGS	01Mar25/06:08	10
03A	UCB	01Mar26/04:43	10	01Mar26/04:54	20	03B	DGS	01Mar26/05:16	10
04A	UCB	01Mar27/06:08	10	01Mar27/06:18	20	04B	DGS	01Mar27/06:45	10
05A	UCB	01Mar30/03:53	10	01Mar30/04:06	20	05B	DGS	01Mar30/04:26	10
06A	UCB	01Apr01/02:06	10	01Apr01/02:24	20	06B	DGS	01Apr01/02:44	10
07A	UCB	01Apr03/05:43	10	01Apr03/05:53	20	07B	DGS	01Apr03/06:19	10
08A	UCB	01Apr07/05:49	10	01Apr07/05:59	20	08B	DGS	01Apr07/06:26	10
09A	UCB	01Apr08/03:29	10	01Apr08/03:42	20	09B	DGS	01Apr08/04:02	10
10A	UCB	01Apr09/04:16	10	01Apr09/04:28	20	10B	DGS	01Apr09/04:49	10
11A	UCB	01Apr10/22:56	10	01Apr10/23:06	52	11B	UCB	01Apr10/23:58	10
12A	DGS	01Apr13/08:24	10	01Apr13/08:34	52	12B	DGS	01Apr13/09:26	10
13A	DGS	01Apr14/13:16	10	01Apr14/13:26	52	13B	DGS	01Apr14/14:18	10
14A	UCB	01Apr15/18:16	10	01Apr15/18:26	52	14B	UCB	01Apr15/19:18	10

Table 1. Ground station contact schedule during orbit-raise. Shown are contacts during reorientations prior to, and after orbital-maneuver fires.

A single pulse of the thruster recurs every 9 seconds and results in a 2 degree spacecraft reorientation. The response time of the near-real time link and the system operator is also on the order of a few seconds. The link margin and gain pattern of the QUATRO spacecraft should (and does) take such simulations into account to allows survival of the spacecraft through cumulative offset due to inadvertent mispointing during several thruster pulses, i.e., ~10^o.

Station: UCB	DOWNLINK		UPLINK
	SCIENCE DATA	ENGINRG DATA	COMND DATA
Frequency [MHz]	2210.000	2210.000	2040.000
Wavelength [m]	0.136	0.136	0.147
TX Transmit Power [W]	2.000	2.000	100.000
TX Cable Loss [dB]	3.100	3.100	2.000
TX Antenna Size [m]	0.059	0.059	10.000
TX Antenna Eff. [%]	100.000	100.000	55.000
TX Antenna Gain [dBi]	2.700	2.700	44.000
TX EIRP [dBW]	2.610	2.610	62.000
Range [km]	20000.000	80000.000	80000.000
Path Loss [dB]	185.360	197.400	196.700
Atmospheric Loss [dB]	0.100	0.100	0.100
Polarization Loss [dB]	3.000	3.000	3.000
Pointing Loss [dB]	2.000	2.000	2.000
RX Antenna Size [m]	10.000	10.000	0.064
RX Antenna Eff. [%]	55.000	55.000	100.000
RX Antenna Gain [dBi]	44.700	44.700	2.700
RX Receive Pow. [dBm]	-113.150	-125.190	-107.100
RX Receive Volt. [uV]	0.492	0.123	0.987
RX Cable Loss [dB]	1.000	1.000	3.100
RX Rcvr Noise Fig. [dB]	0.600	0.600	5.000
RX Antenna Temp. [K]	20.000	20.000	100.000
RX System Temp. [K]	158.941	158.941	1726.011
RX Receiver G/T [dB/K]	22.690	22.690	-29.670
Data Rate [kbps]	200.000	2.000	2.000
Modulation	BPSKR1/2VD	BPSKR1/2VD	FSK
Bandwidth [kHz]	400.000	4.000	4.000
Bit Error Rate	1.0E-05	1.0E-05	1.0E-05
Required Eb/No [dB]	4.400	4.400	13.300
Predicted Eb/No [dB]	10.530	18.490	26.220
Implem. Loss [dB]	1.000	1.000	2.000
Predict. Link Margin [dB]	5.130	13.090	10.920

Table 2. QUATRO spacecraft link margin.

4. COMMUNICATIONS

A schematic of the spacecraft telemetry system commensurate with the data rates required by the science is shown in Figure 8. Two body-mounted, ground plane antennas (top: 3/4 λ, bottom: 1/4 λ, where λ is wavelength) at a permanent 9:1 power split optimize the gain pattern resulting in good uniformity (Figure 9) and a maximum gain of 2.7 dBi. In particular Antenna patterns were run by EE student Yuri Yuriev using first EZNEC and, under GSFC supervision, using the High Frequency Structure Simulator (HFSS). The antenna simulator incorporates a realistic model of the spacecraft and is the last step before the anticipated antenna tests at GSFC. An S-band frequency is used (2200 MHz) with a wavelength that is comparable to the spacecraft dimensions. The HFSS runs were necessary because although a single antenna cannot guarantee a uniform gain, multiple antennas interfere due to diffraction of radiation around the spacecraft causing interference nulls as a function of both azimuth and elevation.

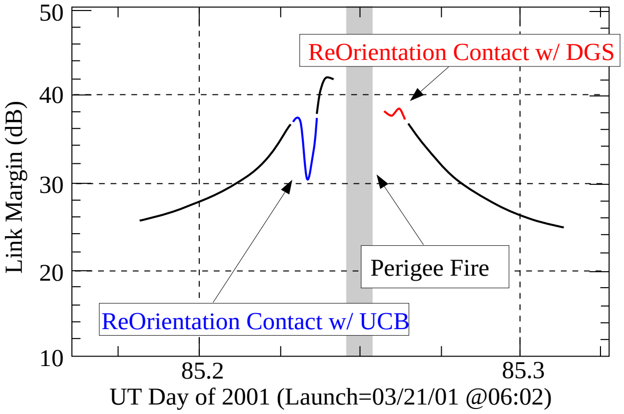

Figure 7. Link margin during a perigee fire taken from the L&EO simulation of Figure 5 and with a realistic gain pattern from two dipole antennas (derived in Section 4).

A single antenna with the benefit of diffraction actually has a quite acceptable uniformity and its simplicity is very attractive. An optimized two-antenna pattern does a better job in terms of uniformity than a single antenna, although the drawback is the added complexity and weight it entails. Although the final decision on antenna pattern can be made after antenna range tests using a spacecraft mock-up are completed, herein we are assuming a two-antenna solution. The pattern's uniformity enables engineering data downlink and command uplink at all distances and science data inside of 20,000 km range. The pattern was designed to allow communications with adequate link margin through +-60 degrees of mispointing at any range.

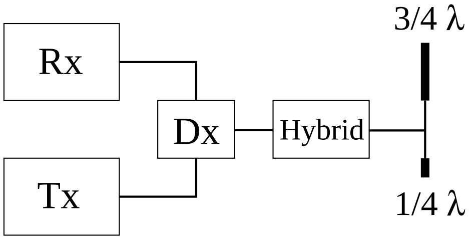

Figure 8. Schematic of the spacecraft RF system.

One can identify several flight-proven parts solutions to the schematic of Figure 8; final selection depends on cost (\$150-\$400 K per complete system, per microspacecraft), weight (1-5 kg), flight history or delivery schedule (6-13 months). The approach taken for the benefit of Constellation is to chose the lowest cost, and weight solution that still meets the specifications of an acceptable link margin.

We selected a receiver that can accept an uplink modulation scheme of FSK, because such receivers are based on lightweight, robust and inexpensive, FM technology. The transmitter is such that it supports a downlink modulation of BPSK directly on a carrier. Because such transmission is based on phase-coherent detection it permits signal detection with even lower bit-error-to-noise ratio than FSK. This enhances the downlink data rates of science data transmission precisely where it is necessary. The diplexer is based on existing design but uses smaller resonant isolation cavities to conserve weight, albeit with an affordable loss of 2dB of link margin. Convolutional, rate-1/2 Viderbi encoding is applied, and increases link margin by 3 dB. The above modulation schemes are compatible with NASA ground stations.

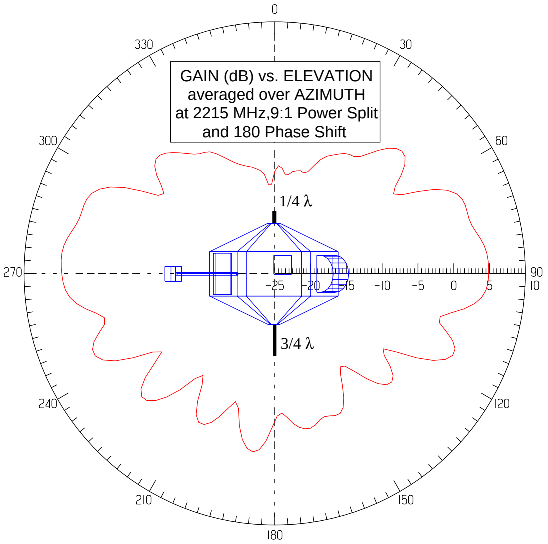

Figure 9. Gain pattern resulting from a realistic QUATRO spacecraft (i.e., including deployed boom and mounted instruments), and using two antennas (1/4 wavelength on top and a 3/4 wavelength at the bottom) and a 9:1 power split.

Typical science data are downlinked inside of 20000 km at 200 kbps with acceptable margin (Table 2). Engineering data, even when downlinked from (or uplinked to) apogee at 80000 km are also communicated with sufficient link margin. Both margins are large enough to account for antenna inadvertent mispointing during L&EO procedures as shown in Figure 7. The actual science downlink margin is range-dominated and for typical science downlink orientations it exceeds the margin quoted in Table 2.

5. ORBIT AND ATTITUDE OPERATIONS

Orbit and attitude solutions are a primary function of tracking and mission operations. For orbit determination, the ground antenna tracking angles are sufficient for deriving the spacecraft position with the desired accuracy of 100 km knowledge at apogee. In fact, the diffraction limit of a 10m antenna is very close to the desired resolution in orbital parameters.

A novel technique for orbit determination is also usable on QUATRO and other constellation spacecraft. The technique produces Doppler-ranging-like accuracies without expensive and heavy coherent transponders. It employs a ranging algorithm on the encoded data, rather than on the subcarrier signal. The method has been used successfully on the Oscar 10, 13 and 20 satellites [J. Miller, 1997]. A variant of the technique is being tested by GSFC on FAST, [Everett and Carlson, 1997] with the anticipation to lead to a NASA standard.

Error Source	**Error**	**Type**
Bit thermal noise	43 m	Random
Ionospheric delay	<25 m	Bias
Ground RF, Cables	<20 m	Bias
Clock Stability	15 m	Bias

Table 3. Error analysis for QUATRO ranging.

In “ranging mode” a unique signal (e.g., time) is sent using the 4 kbps, encoded uplink data rate. The received signal on the spacecraft is retransmitted without deconvolution or decoding but with a prespecified and fixed relay time. For a clock drift rate of 10^{-5} on a relay time of 1 msec the range error is 15 m. The one-sigma range measurement error coming from bit detection noise is: $\sigma_R = (c/2D_R) \bullet \sqrt{P_N/(4P_S N)}$, where D_R=data rate, P_N (P_S) is noise (signal) power and N is samples averaged. For 1 second transmission of 4 kbits of convolutional-encoded bit stream and for QUATRO specifications σ_R=43m. Total random errors are less than 50 m and bias errors are less than 70 m. From 1 min ranging per contact over 20 days, position knowledge at the next contact of 1.1 km and speed knowledge of 0.16 m/s are achieved (one sigma). During L&EO the orbit can be determined after each burn assuming 6 contacts of 1 min duration every ~3 hours, or fewer contacts of longer duration. The energy available for transmission allows ranging sessions in excess of 10 minutes; the above number of contacts is thus an upper limit. Both during both L&EO and science phase an accurate and stable orbit solution can be achieved with this simple, inexpensive scheme, with heritage in AMSAT practices.

SENSOR	TYPE	SINGLE SPIN RES.	FOV (Spin Plane Elevat.)	MEASURED QUANTITY	SPIN OR ORBIT AVGD RESOL.
1 Fine Sun	V-slit	0.5	0+-60	Sun: θ, ϕ	0.2
1 Fine Earth/Moon	HCI (IR slit)	0.15-0.5	0+-55	Earth/Moon:ϕ	0.1-0.3
3 Crude Sun	Solar Cell	5	0+-90	Sun: θ, ϕ	3
1 Magnetometer	3axis Fluxgate	1	0+-90	BField:θ	0.3: θ , ϕ

Table 4. QUATRO attitude sensors

The science requirement on attitude determination is 1^{o} knowledge. Attitude determination is easily achieved by a combination of data from a V-shaped fine sun sensor and a fine Earth and moon sensor (IR-detector). Additional, crude sun sensors provide 4π coverage, 3^{o} resolution, essential during L&EO. Error analysis on the full attitude solution shows that the orientation will be known at all times to within 0.5 degrees (three sigma) or better. Backup fine attitude information relative to the magnetic field at low altitude will also be obtained from the magnetometer sensor. When combined with orbit modeling it will also result in full spin axis information to 0.3° or better. Cross-calibration of the sensors (mounting offsets, magnetometer gains) will take place in the first few engineering data downlinks. A Matlab-based graphical user interface that performs attitude determination from Sun and IR data called Multimission Spin Axis Stabilized Spacecraft (MSASS) developed by GSFC and has been ported to UCB for such analyses. This program forms the core of the mission operations center attitude solution scheme, both in real time and in a post-processing mode.

Attitude determination during science operations is simple because QUATRO has a stable spin direction. Only shadows can possibly influence the spin rate. Shadow durations are kept to less than 90 minutes for thermal control reasons [Delory et al., 1998] and occur at most once per orbit. Since shadow data losses incurred are minimal we do not expend any resources to overcome such situations.

In summary, orbit determination using Doppler ranging requires a 1 minute-long ranging session for every contact during science and L&EO operations. The convergence of the orbit solution is robust and quick, much like using traditional ranging techniques. Attitude determination requires processing of IR and Sun sensor data, with programs that are currently in use and provide either real time or postprocessing attitude solutions.

Spacecraft control during L&EO operations has been modeled (Section 3) in the absence of fuel motion using GMAN. Fuel behavior also requires modeling in particular if no provision is taken to minimize slosh or inertial waves. Addition of baffles within the tank is a first step towards making the problem tractable. Graduate student Fayez Khan as a part of his master's thesis is studying this problem. Modeling the fuel behavior with a rotating disk model, most applicable to vertically positioned baffles, results in an efficient algorithm. This simple model will be verified against CFD analysis and will be integrated into an existing dynamic spacecraft simulator which has been validated on other spinning spacecraft.

6. MISSION AND SCIENCE OPERATIONS

Figure 10 describes the functions to be performed by the mission operations center (MOC) and science operations center (SOC) systems during L&EO and science phase of the mission. The same functions are necessary for instrument and spacecraft integration and testing (I&T); thus it makes sense that a common system be used for all those functions. The ITOS package (Integrated Test and Operations System) built out of GSFC/SMEX practises and employed successfully for FAST, and now also HESSI, operations, satisfies these requirements. The Spacecraft Command and Telemetry (SCAT) system, that functions as a spacecraft front-end will be used for I&T and for ground station commanding. Implementing ITOS and SCAT is easy and cost-effective as they are built on COTS components and NASA-developed software.

It is commonplace on FAST, TRACE and other SMEXes to not have an MOC operator monitor each data dump, but rather to automatically send the commands and schedule updates to the antenna site. TRACE also implements unsupervised post-processing, checking of instrument and health status and automatic on-call operator paging. This situation has resulted in efficient MOC operations. Antenna operations can be performed in a similar way, i.e., with automatic commanding, pointing, data retrieval and processing, to validate

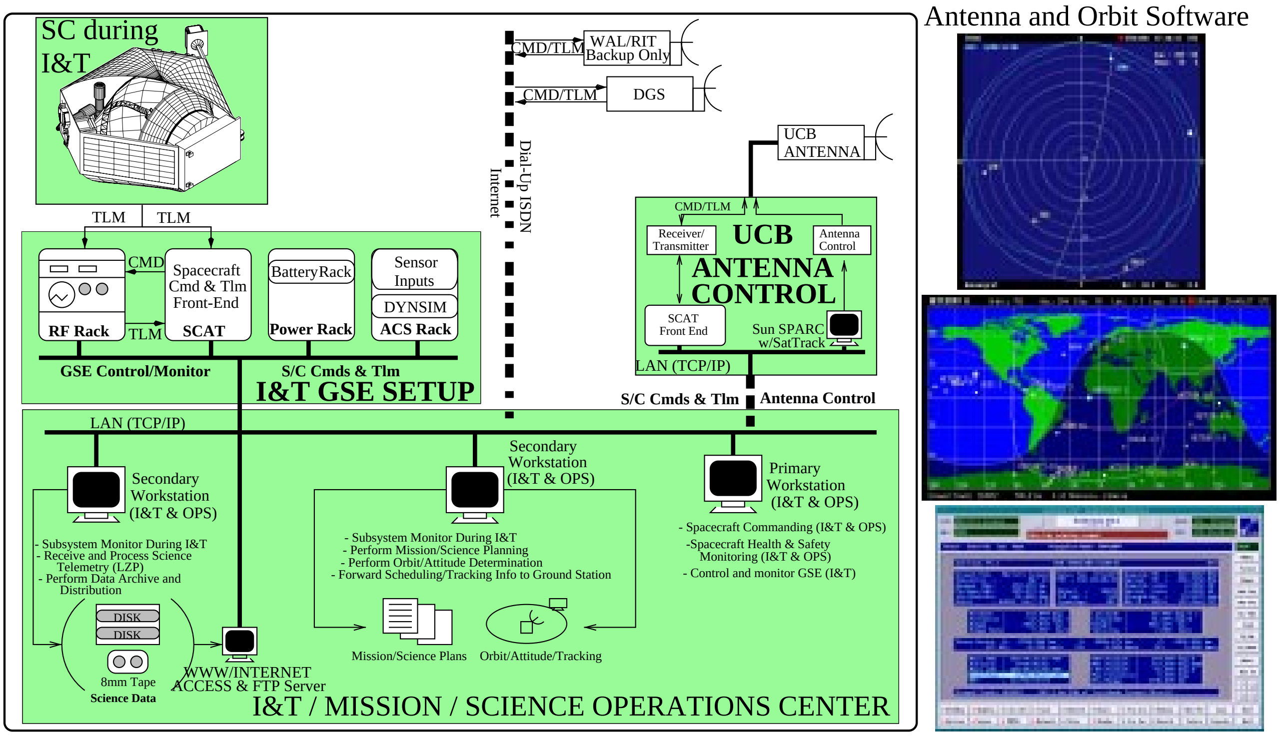

Figure 10. The mission and science operations center for QUATRO spacecraft, which can serve as an integration and testing facility. It is built using ITOS and SCAT, developed at GSFC/SMEX and using low cost, robust commercial components and mission-proven NASA-developed software. It has been used by SMEX on FAST and TRACE and it is being duplicated for UCB antenna operations on the HESSI spacecraft.

the pass parameters and page a live operator in the case of off-limits operation. The above practices will be implemented on the HESSI mission. They are expected to reduce significantly the cost per 10 minute-duration pass to a small fraction of ~$400; the figure of merit for a TOTS antenna.

The fact that all instruments have a common DPU simplifies integration and testing, because no separate testing is required for instrument-main-computer compatibility. The entire suite of instruments will undergo thermal, vibration testing together with the spacecraft. This entails placing the entire spacecraft in a thermovacuum chamber, like a single instrument. The size of the QUATRO spacecraft is such that a small thermovacuum chamber can enclose it, further reducing pump-down time.

Each spacecraft transmits 15MBytes of data per pass. A year's worth of data from the QUATRO mission, utilizing a single ground antenna (i.e., at 55% coverage) results in a volume of 12Gbytes, which can fit easily in a single hard drive, and is comparable to 10 days of FAST data. The internet is the most appropriate means of data exchange of such data, while a WWW-based retrieval is more than adequate for the mission.

7. SCALING TO A POPULUS CONSTELLATION

Operations of Constellation spacecraft depend on the method of ascent chosen. Available options are i) an autonomous mothership starts from GTO and releases several tens of ~5 kg microspacecraft that do not have propulsion capability and ii) the upper stage of the main launch vehicle releases at GTO the ~20 kg microspacecraft, which then use their own propulsion systems to propel themselves to their final orbits. A breakdown of the QUATRO mass budget reveals a figure of merit to be used to judge the efficiency of the two schemes: On QUATRO, 4 kg are expended on the propulsion system components, 8 kg on the suite of instruments, structure, harnessing and other spacecraft subsystems and 9 kg (75% of the dry mass) are allocated for propellant. Based on the above breakdown, an mothership equipped with propulsion should be able to deliver to their final orbit a microspacecraft mass equal to 38% of the wet, loaded mothership that is released at the initial GTO.

Assuming a mothership with orbit-raise capability, L&EO operations are significantly simplified because no in-orbit testing of 60 propulsion systems is required, and only a single launch vehicle is commanded through the ascent operations, rather than 60 spacecraft one-after-the-other. The cost of the reduced L&EO operations should be compared against the cost increase from a rather traditional propulsion system with built-in redundancy, quality assurance and high-level operations. Today neither fully automated operations of tens of autonomous spacecraft, nor the cost of the autonomous mothership can be approximated from past experience. However, it should be noted that two antidiametrically located 10m diameter primary antennas are necessary and sufficient for Constellation operations. The cost of buying time on existing antennas should be compared with the cost of the 11m antenna turn-key system construction, constructing and manning the MOC and SOC center, and preparing for HESSI operations at UC Berkeley which is on the order of $3M. Out of that the antenna cost is $1.6M.

The science downlink schedule of contacts for Constellation is naturally more demanding by an order of magnitude relative to QUATRO. Figure 11 shows how stations UCB and DGS can accomplish 95% of the data return from 60 microsatellites assuming 12 minute contacts, and orbits with the same, low perigee but apogees ranging from 12 to 42 Re. This is a classical situation where automated antenna operations can result in significant cost savings. Conflict resolution between passes can be implemented first on a pass-by-pass basis (this was done in Figure 11) and in an automated fashion, after parametrizing the orbit's significance for science.

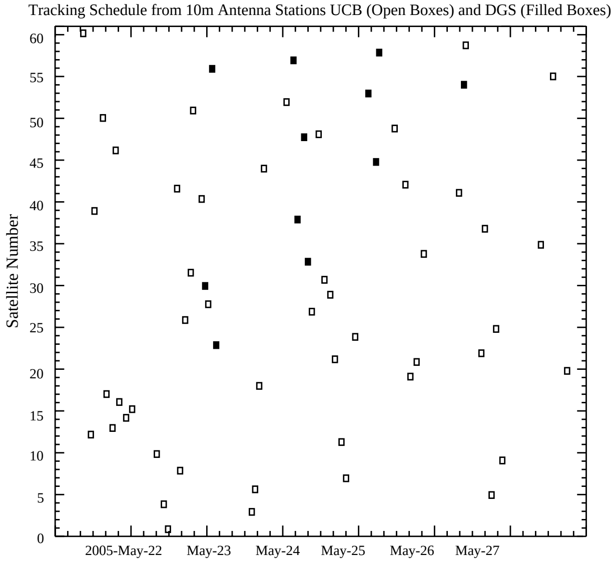

Figure 11. Typical schedule of contact times for Constellation mission using two anti-diametrically located ground stations to downlink 96% of the mission data.

Given the low data rates from Constellation class microspacecraft, even full coverage of all data from all probes once per orbit still results in a data rate of 0.3 Gbytes/day which is 4 times smaller than that of the FAST satellite.

The economy of scale results in reduction in amortized development cost. A large number of identical microspacecraft provide risk mitigation, and graceful mission aging, eliminating otherwise expensive solutions that would have to provide multiple redundancy. Parallel testing is possible e.g., by building more than one I&T equipment racks, and utilizing the same thermovacuum chamber. Finally, efficiency that is more difficult to quantify comes from commonality in throubleshooting. Taking advantage of the telecommunications and defence industry's experience in this area can be beneficial for planning the Constellation operations.

8. DISCUSSION

The above discussion utilized QUATRO as an example of a Constellation protoflight that can result in significant science return with a small downpayment. The real advantage, however, to the successful funding and implementation of such a program lies in its ability to prove in a show-and-tell fashion how big science can be conducted from small satellites. Such pathfinder missions are invaluable scientifically, for clarifying our understanding of the scale sizes and processes that are to be explored with more populous missions, but also technologically, as they will provide the much needed point of reference for the cost benefits assumed by the economy of scale.

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