A high science return, low cost, Constellation pathfinder

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A fundamental limitation in observational space physics arises out of the inherent ambiguities between spatial and temporal features that are present whenever measurements are conducted from a single platform. In this work we describe the QUantitative Assessment of magnetospheric TRanspOrt (QUATRO) mission concept, which intends to utilize identical instrumentation on four small Earth-orbiting spacecraft in an effort to resolve some of the fundamental questions that are currently still debated in magnetospheric physics. The primary research area intended for QUATRO is the timing and trigger for the geomagnetic substorm. A well-focused orbit and instrument design towards the primary science objective also allow QUATRO to study the energy coupling between the solar wind and the magnetosphere, as well as the transport and acceleration of energetic radiation belt particles during magnetic storms. The QUATRO mission concept maximizes cost effectiveness and science return by using flight proven commercial off-the-shelf technologies and science instruments integrated on a single data processing unit. QUATRO is designed to be launched as a co-manifest payload on Geosynchronous Transfer Orbit - bound launch vehicles which reduces the launch cost and provides frequent low-risk flight opportunities on future commercial and military launches.

1. INTRODUCTION

The desire to obtain simultaneous, multi-point measurements from spacecraft within the magnetosphere was realized from the dawn of space age and has received significant attention following the completion of the ISTP program [Angelopoulos and Spence, 1998]. This desire is driven not only by the limitations of the current data sets, but also by the increasingly available access to space, due in large part to boom of the commercial satellite industry. The latter has resulted in an unprecedented number of secondary launch opportunities, in which small payloads may "hitch a ride" on existing planned missions [Rademacher and Leschly, 1996]. The advent of the "micro-sat" concept, which takes advantage of instrument miniaturization and increased reliability of commercial-off-the-shelf (COTS) components to driven the spacecraft mass to much lower levels, makes the inclusion of these spacecraft as secondary payloads all the more feasible. Because of their smaller size and shorter development time such spacecraft can be built and launched at a significantly lower cost than traditional ones.

The proposed QUATRO mission serves a dual purpose: First, by virtue of its well focused instrumentation and orbit it will perform much needed multi-point measurements in the Earth's magnetosphere and resolve outstanding questions in the field of space physics. By exploring the scale size of important geophysical processes it will lay the ground work for mission planning of more populous constellation class missions. Second, it will serve as a technology demonstrator for future, more ambitious constellation missions by demonstrating the feasibility of a scientifically rewarding, low-cost, low weight autonomous micro satellite.

2. SCIENCE OBJECTIVES

2.1 Particle acceleration in the magnetosphere

The primary science goal of the QUATRO mission is to understand the cause-and-effect relationship between the processes that are associated with the geomagnetic substorm. Substorms represent explosive releases of magnetospheric energy which has accumulated from the coupling of the solar wind to the Earth's geospace. They are a fundamental mode of magnetospheric variability, shaping space weather much in the same way that the formation, motion and decline of a cyclone affects atmospheric weather [Siscoe, 1997].

Magnetic reconnection, in which two regions of significantly differing magnetic field geometries interconnect across a boundary, has been proposed to play a major role in substorm development by being responsible for releasing the large amount of solar wind magnetic energy stored in the magnetotail [Hones et al., 1976]. The spatial scale over which this process may occur ranges from 15 to 30 Re [Nagai et al., 1997]. In association with magnetic reconnection are fast Earthward-directed flows of plasma moving close to the Alfven speed (~1200 km/sec) which may be a result of the tailward reconnection site [Angelopoulos et al., 1994]. These "bursty bulk flows" (BBFs) have been shown to be responsible for a significant amount of the energy and flux transport in the magnetotail. A second key process observed in conjunction with the substorm is the formation of the "substorm current wedge" [McPherron et al., 1973] roughly 7-10 Re out in the magnetotail. In this phenomenon, currents which are self-consistent with the flux content of the tail lobes and which normally close across the tail region are suddenly disrupted and are diverted into the auroral ionosphere. Thus this process has also been called "current disruption" [Lui et al., 1996]. It is fairly well known that the first substorm auroral arc that brightens is magnetically connected to the region of the current wedge formation; what is not understood is what initiates this process.

Single spacecraft missions have revealed that reconnection, bursty flows and current disruption are key magnetospheric processes partaking in the formation, evolution and eventual energy deposition during an auroral substorm. But the fundamental questions of the how and why of substorms are still left unanswered: What causes the onset of a substorm in the magnetosphere? What controls the timing of this onset? What determines the onset location?

Given the combination of processes described above, there are currently two major competing paradigms of substorm onset and evolution which the QUATRO mission aspires to resolve and study. In the first paradigm, known as the "Near-Earth neutral line" model of substorms, it is the onset

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of magnetic reconnection in the tail that causes a sudden onslaught of Earthward plasma flows in the form of BBFs [Figure 1]. As these flows impact the inner edge of the plasma sheet at 7-10 Re, the kinetic energy of this bulk flow of plasma is translated into increased particle heating and vorticity, and is responsible for a pile-up of transported magnetic flux in the near Earth region. This is tantamount to a disruption of the cross-tail current and hence current wedge formation. The resulting field-aligned currents are then responsible for the auroral substorm breakup.

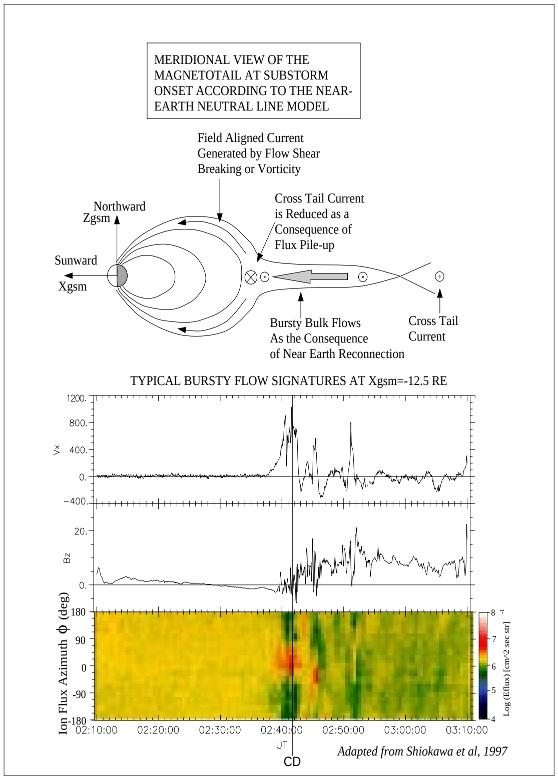

Figure1. Near-Earth neutral line paradigm of substorm onset and supporting data. Current disruption and substorms develop after the fast flows have started.

A second model for substorm dynamics assumes that there is an inherently local plasma instability that causes the disruption of the cross-tail current in the 7-10 Re region [Lui et al., 1996]. In this case the energy released during a substorm is initially stored in the particles carrying the cross-tail current. The observed Earthward flows and reconnection at ~20 Re distance are initiated by the tailward motion of the localized instability. Hence they should be observed after the current disruption has started at 7-10 Re. This is called the "current disruption" model of substorms.

The present ambiguity between these two models results directly from the scarcity of observational data from multiple satellites which could observe the causal relationships of the processes that are well established and studied using comprehensive single satellite missions [Kennel, 1992; Angelopoulos, 1996].

The QUATRO mission aspires to resolve the cause-and-effect relationship between current disruption, reconnection flows and substorms, using correlated measurements from four spacecraft [Figure 3]. All four spacecraft have a common 1500 km perigee altitude. Two spacecraft (Q1 and Q2) will be in an elliptical orbit with an apogee of 11.5 Re, while the other pair (Q3 and Q4) will be placed in a higher orbit at 12.5 Re. The Q1 and Q2 spacecraft in the lower orbits will have different inclinations of ~2.5 degrees, so that these spacecraft are separated by ~0.5 Re along the z-direction at apogee. The QUATRO pair at the higher apogee will have a phase lag of ~13 degrees in their mean anomaly, so that these spacecraft will be at a ~0.5 Re separation along their orbit at apogee.

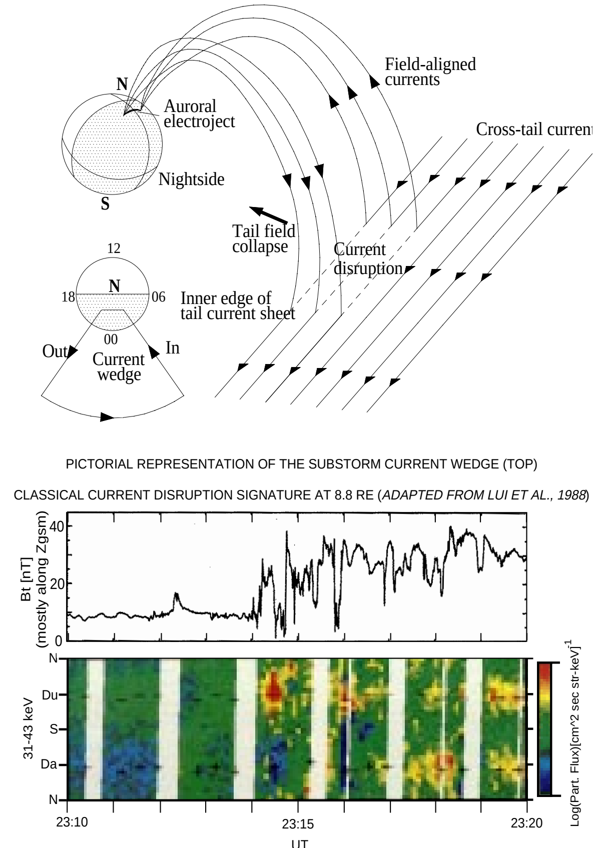

Figure2. The substorm current wedge (top) and supporting data of the "Current Disruption" paradigm of substorm onset (bottom).

The results of this relative orbital configuration between all four spacecraft are 3 different geometries relevant for conducting multi-point measurements in the Earth's tail: A "clustered" configuration, in which all four spacecraft form a tetrahedron at apogee, roughly 0.5 - 1 Re on a side. An "aligned" configuration, in which the two pairs of spacecraft are separated by several Re along the Sun-Earth direction (GSM X) in the tail. A "cross-tail" configuration in which the two pairs of spacecraft measure simultaneously across the tail, separated primarily in the Y-direction. All four spacecraft possess identical instrumentation, namely an ion and electron electrostatic analyzer for imaging the energetic particle distributions, a 3-axis fluxgate magnetometer, and a solid-state telescope for measurements of the most energetic MeV particles.

QUATRO will resolve the cause-and-effect relationship between current disruption, bursty plasma flows, and substorm onset. Once the time-sequence of substorm onset in the magnetosphere has been established, future theoretical investigations and analysis of existing datasets will be able to focus in the right spatial region and time scale. To accomplish this leap in our understanding of the substorm process, QUATRO will use its frequently occurring tail-aligned (within 22.5˚ of the tail axis) geometry to directly measure the Earthward propagation of fast plasma flows and/or the tailward propagation of the current disruption process. Additionally, it is hypothesized that fast-mode waves generated by anti-Earthward current disruption expansion may propagate out and initiate reconnection in the tail. These waves can also be measured and identified when QUATRO is in the tail-aligned configuration.

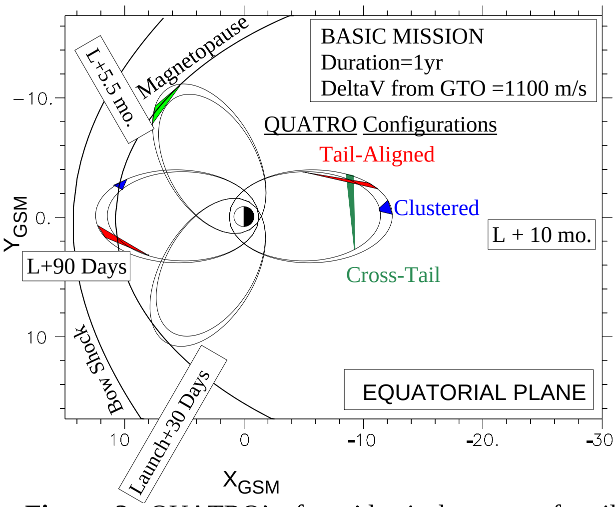

Figure 3. QUATRO's four identical spacecraft will study the equatorial magnetosphere in all three dimensions simultaneously and resolve the spatio-temporal ambiguity that riddles substorm research.

By studying the number of possible conjunctions between the four spacecraft we can determine the amount of time that any two QUATRO spacecraft will be in a tail-aligned configuration. This is shown in Figure 4. Since more than 500 hours of data will be available from the first year of operation, and assuming a substorm recurrence rate of one every 3 hours, we conclude than even with a 50% data return from the QUATRO mission more than 80 substorms will be studied by a tail-aligned configuration. This is an order of magnitude improvement over fortuitous conjunctions between current spacecraft.

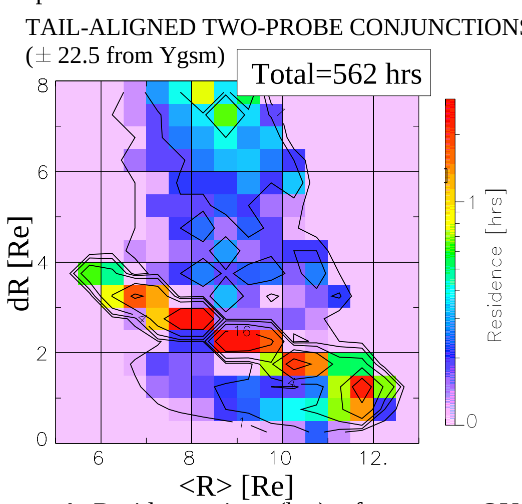

Figure 4. Residence time (hrs) of any two QUATRO spacecraft at a tail-aligned (within 22.5° of the tail axis) interspacecraft separation. The residence time is plotted as a function of two parameters: The radial distance of the center of mass of the spacecraft <R> and the interspacecraft distance dR. Total time in this configuration is 562 hrs.

If QUATRO determines that it is the tailward reconnection that occurs first, causing the sudden Earthward BBFs which then disrupt the cross-tail current, the mission will further be able to verify that the amount of energy associated with these fast flows is consistent with the magnitude of the associated auroral substorm.

This can be done by examining the scale size of the flows with two or more QUATRO spacecraft in the "cross-tail" configuration, combined with information using remote measurements from Solar Wind and UV data acquired by the ACE and POLAR platforms which should yield an estimate of the energy released in the auroral ionosphere.

If it is determined that a local instability within the current sheet is responsible for current wedge formation, and thus the subsequent substorm activity, QUATRO will be able to identify the exact nature of these processes by combining high-resolution in situ plasma and magnetic field measurements on each platform.

Currently there are two major candidates for such an instability in the current sheet: Ballooning/Interchange Instabilities (BII) and Cross Field Current Instabilities (CCI.) The BII's are generated by the large pressure gradients expected in the near-Earth plasma sheet and may have wavelengths on the order of 2000-12000 km, moving azimuthally with the diamagnetic drift speed of the ions (50-100 km/s). Multiple QUATRO spacecraft with azimuthal separations in the "cross-tail" orbital configuration would be able to measure these coherent waves using standard cross-spectral techniques. CCIs, on the other hand, have no azimuthal coherence but may have wavenumbers along the magnetic field, with frequencies below the local lower-hybrid resonance and wavelengths of 300-2000 km. QUATRO spacecraft in the "aligned" configuration will be able to measure these waves. Thus should an inherent instability prove to be the "smoking gun" of auroral substorm activity, QUATRO will be able to distinguish between the two most prominent possibilities, which will focus the attention of future theory and modeling on the correct mechanisms most relevant to substorm generation.

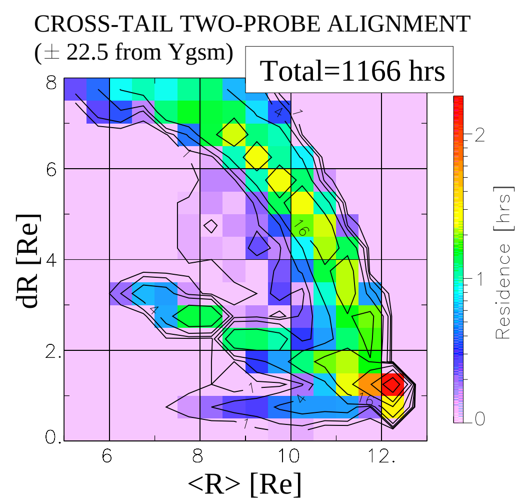

Figure 5. Residence time (hours) of any two QUATRO spacecraft at a cross-tail (within 22.5° of the Y_{GSM} direction) interspacecraft separation. The format is the same as in Figure 4. Total integrated time in this configuration is 1166 hours.

2.2 Magnetopause and radiation belt science

Although QUATRO's orbit and instrumentation were optimized for substorm studies, QUATRO is uniquely suited to provide answers to outstanding questions at two other regions that it will visit: The magnetopause and the radiation belts.

QUATRO SCIENCE REQUIREMENTS	
Timing of 2000 km/s speed signal between CD and BBFs, over 1-5 Re SC separations: => Need 3sec resolution	Baseline 2s spin rate exceeds that.
Routinely monitor the cross tail sheet current	Q 1 & 2 separated by 0.5 Re.
B field @ 1 sample/spin Plasma moments in tail @ 1 sample/spin Distribution functions and energetic particle spectra at full resolution during fast flow or dipolarization events.	Planned data accumulation rate exceeds that.
B field relative accuracy to 1 nT and moments relative accuracy to 10% Orbit knowledge to 10% of S/C sep.	Standard Fluxgate and ESA calibration exceeds that. Orbit knowledge requirement satisfied by tracking requirements.
Keep interspacecraft separations in range of 0.2-5 Re: Requires stability of orbit configuration: Q1-Q2 within Δ(inc)~+2.5deg Q2-Q3 within Δ(T)~+2.5 hrs Q3-Q4 within Δ(ma)~13 deg.	Orbit stable to J2, lunar and other perturbations. Orbit placement will be fine-tuned during L&EO; orbit solution converges through either ranging or ground tracking angles.

Table 1. QUATRO science requirements.

At the magnetopause QUATRO will determine the boundary conditions, extent, and effects of reconnection over scale-lengths between 0.3-8 Re, utilizing more than 700 hrs of 2 and 3 spacecraft magnetopause azimuthal conjunctions.

At the radiation belts, QUATRO will be able to determine the source of MeV electrons at storm recovery. The rapid replenishment of radiation belt electrons at storm recovery represents the largest electron flux increase during the entire progression of the storm. The mechanism for rapid (~4 hours) acceleration of those electrons is an outstanding question in radiation belt dynamics today. QUATRO will determine whether radial transport is responsible for the observed rapid flux increase by measuring the radial profile of equatorial energetic electrons from 3 to 12 Re with a fast repetition period: One radial profile will be acquired by any QUATRO spacecraft every 2.5 hours, i.e., at a time scale commensurate with the MeV electron energization. This frequent radial profile acquisition is made possible only because of the existence of multiple spacecraft, since a single spacecraft scans the radiation belts only every 12 hours.

2.3 Science requirements versus instrumentation

The mission requirements stemming from the primary science objective (substorm science) are outlined in Table 1. Science instruments flown on current missions easily exceed the QUATRO requirements. A low-cost approach to the QUATRO mission calls for re-utilization of existing designs, since the primary methodology for achieving the mission goals is not advanced instrumentation but rather a well focused orbit design following careful mission analysis.

The QUATRO platform will be spin-stabilized with the spin axis normal to the ecliptic plane and a spin period of 2 seconds. Each spacecraft will be equipped with three science instruments: An electron/ion electrostatic analyzer (ESA) measuring the 3 dimensional ion and electron distribution in the range of 3-30 KeV, once per spin. A fluxgate magnetometer (MAG) producing 16 vector magnetic field measurements every spin period, at an absolute resolution of 1 nT. A solid-state telescope (SST) with two look angles, at 30 degrees above and below the spin plane, each with a 15 degree field of view. Each detector will measure electrons and ions in the 20 keV-1MeV range and its pointing eliminates sun-light while being close enough to the ecliptic plane to monitor the ~90˚ pitch angles in the ring current as well as the high speed flow flux increases seen beyond the ESA energy range. The instruments are based on existing designs as shown on Table 2.

INSTRUMENT	WGT (gr)	PWR (mW)	HERITAGE
ESA, w/ High Voltage & Analog Electronics	2,015	1,260	FAST Sensor
SST with High Voltage & Analog Electronics	481	400	WIND Sensor
MAG, Sensor Feedback, Drive & Digital Circuitry	480	600	FAST Sensor

Table 2. QUATRO spacecraft instruments.

The relative orbital separations remain within prescribed limits because the orbits were designed to be robust to second order corrections. This is achieved as a result of a common perigee for all four orbits (minimizing J2 and drag effects) and the similarity of the remaining orbital elements of the four QUATRO spacecraft. Figure 6 illustrates that point using the Goddard Trajectory Determination System and including all relevant higher order perturbations.

All of the science requirements are met by simple, COTS components. For example, attitude determination is possible to better than 0.2 degrees (one sigma error) using standard sun and horizon sensors, based on an analysis that uses flight-proven sensor data. Orbit determination is possible to within ~1 km assuming a ~1 minute ranging session following each telemetry contact [Angelopoulos et al., 1998]. Backup usage of the tracking antenna pointing angle data can produce the desired orbit knowledge of 10% of the inter-spacecraft separation very quickly within the mission. Spacecraft stability is 1 degree or better by using the central fuel tank as a nutation damper rather than additional nutation dampers. Due to the choice of small thrusters, attitude control is feasible to within 5 degrees. By focusing on a few outstanding science objectives, QUATRO eliminates generic attitude and orbit knowledge and stability solutions that could have been expensive, power hungry and heavy.

Finally, data accumulation that can achieve the mission science objectives results in 120 Mbits of data storage per orbit. The data collection includes routine full distribution function (FDF) recording at a low time rate (once per 40 seconds) but also full or reduced distribution function recording (FDF or RDF) at every spin at times of “burst” data collection. Triggers for burst data recording will be based on existing logic developed for WIND which manages to trigger on all bursty flow and dipolarization events in the near-Earth region, as well as on magnetopause encounters.

The collected data can be stored and dumped during the inbound or outbound leg of the orbit when sufficient link margin is available [Angelopoulos et al., 1998]. To maximize science return from a limited bandwidth we require that data collected at periods when all four satellites were in the magnetosphere receive highest priority for retaining and dumping. Thus a favorable orbit's data which did not transmit to the ground due to lack of station coverage may be recorded on memory and transmitted at a later time, taking precedent over the current orbit's data.

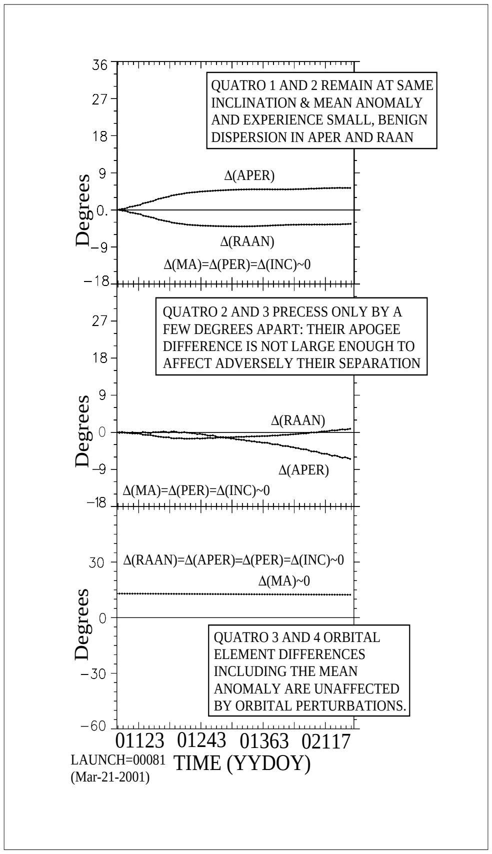

Figure 6. Evolution of QUATRO interspacecraft separation over a 13 month period using the Goddard Trajectory Determination System. The integrator includes J2, lunar, solar and drag effects. The QUATRO formation is robust to orbital perturbations and its constancy depends on the accuracy of the initial orbit placement.

3. MISSION IMPLEMENTATION

3.1 Co-manifest launch opportunity

A near-equatorial orbit for a spacecraft that weighs ~100 kg can be achieved by a single Pegasus launch with an additional solid motor fourth stage. An alternative approach is to use existing rides to the Geosynchronous Transfer Orbit (GTO) and use on-board propulsion to position the spacecraft in their final orbits. The latter is the approach taken in this writeup. We identified a potential launch opportunity with additional lift margin and used that opportunity to demonstrate feasibility of the launch scheme. Nevertheless, the analysis described here can be used on a wide variety of launch vehicles that utilize the Centaur engine as an upper stage, i.e., the Atlas and Titan series launch vehicles.

The co-manifest launch opportunity selected for study was the launch of the GOES-M satellite on an Atlas IIA on July 1, 2001. It has a 394.6 kg of margin over and above the launch contingency allocated to the primary spacecraft. Current estimates of the total weight of the four QUATRO spacecraft complement are 98.4 kg, including an overall 25% mass contingency. Thus the QUATRO mission weight is approximately one fourth of the current throw-weight capability of the GOES-M launch. Lockheed Martin under contract from NASA-LeRC performed a launch feasibility and cost analysis of the QUATRO co-manifest launch, concluding that it is possible to launch QUATRO in the desired orbit (GTO), with the desired initial spin rate (> 30 RPM initial spin) and orientation (spin normal to the ecliptic to within 5 degrees) for the cost of $3.3 M. This represents nearly an order of magnitude cost reduction over a Pegasus launch, which comes with a bonus of an increased accuracy in orbit injection and knowledge. The actual cost may vary depending on the specific type of spacecraft adapter ring used on the Centaur upper stage, as well as on the peculiarities of the primary spacecraft for the particular launch selected. Figure 7 shows the QUATRO spacecraft mounted on the adaptor ring of the Centaur upper stage, and observing all clearance requirements from the various electronic, electrical and mechanical modules that attach to the bracket.

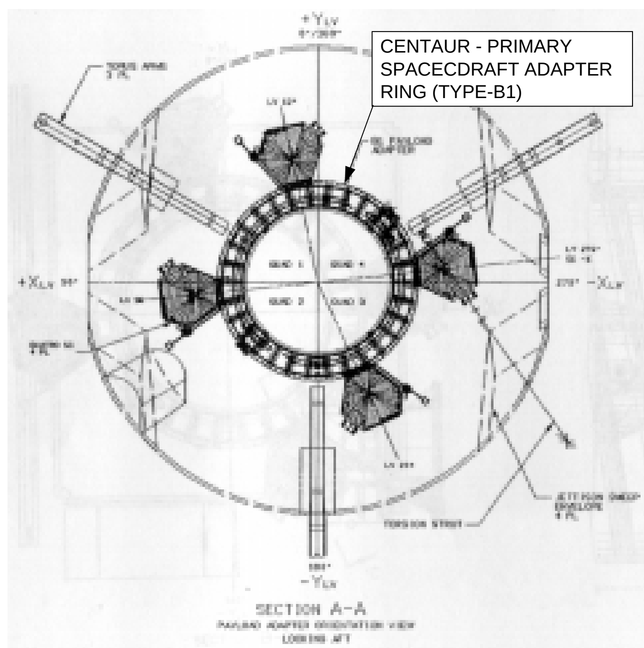

Figure 7. QUATRO mounting on Centaur adapter ring.

The Atlas launch provides a "smooth" ride to the QUATRO spacecraft and attach bracket, such that a simple release mechanism (Figure 8) can carry the ascent and primary separation loads, while providing a robust release and spin-up operation. The release as a function of initial conditions of the QUATRO fuel mass was studied by NASA LeRC, while a parametric study of the location, orientation and strength of the release spring has been completed as a part of a Master's thesis project [Gun, 1998]. Both those studies indicate that irrespective of the initial fuel location a final 30RPM spin rate is achieved (Figure 9), while clearance between the magnetometer boom and the adapter ring or the other QUATRO spacecraft is maintained throughout the release.

It is important to note that prior to the release, propellant settling is achieved via a 5RPM rotation of the Centaur prior to the release. Furthermore, a hinged release mechanism keeps QUATRO spinning only about the Z-axis during the release minimizing effects of fuel slosh. Any nutation present upon release will be readily damped such that the final spin vector will be along the torque imparted by the spring force, because the fuel itself acts as an exceptional nutation damper. To accentuate the operation of the fuel as a nutation damper, we have incorporated tank baffles (not shown here) and we are also considering elastomeric diaphragm, and a separate nutation damper as alternatives.

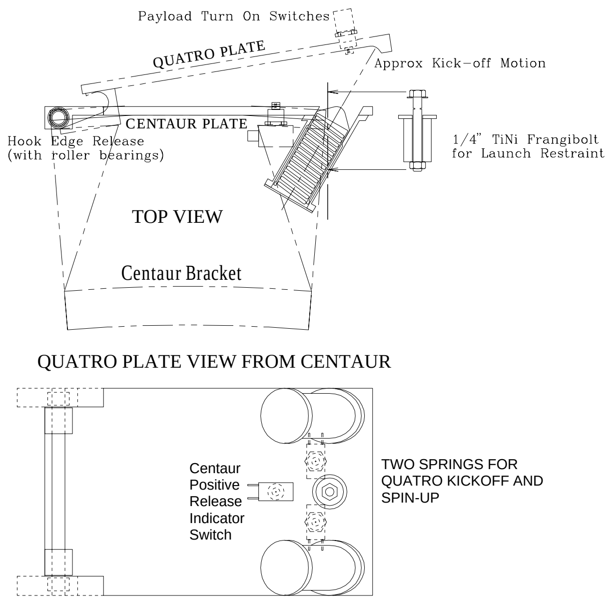

Figure 8. QUATRO mounting and release mechanism.

Following their release to GTO, the QUATRO spacecraft will use their own propulsion systems to raise themselves to their final orbits. Figure 10 shows the orbit evolution from GTO to the final equatorial orbit of 1500 km perigee altitude by 12.5 RE apogee geocentric distance. This requires a total deltaV of 1100 m/s which is achieved with a monopropellant hydrazine-to-dry-spacecraft-mass ratio of 75%. The orbit ascent to the final orbit is described in the companion paper by Angelopoulos et al. [1998]. Its main design was a series of ~14 low impulse maneuvers to be completed over a period of less than a month, through which near-real time telemetry allows continuous checkout of autonomous spacecraft performance without the need for real time control.

3.2 Spacecraft design

Operational simplicity, low risk and usage of off-the-shelf, low cost, and ample heritage components form the basis of the QUATRO design. Instruments were distributed around the tank to maximize dynamic spin balance. Three solar panels in triangular mounting with sensor placement in cut-aways minimize power spin-ripple and shadowing. A common instrument and spacecraft DPU minimizes connectors and is housed in a stiff rectangular Aluminum box, both for radiation shielding and for structural support.

The propulsion system utilizes a monopropellant blowdown hydrazine fuel tank. This is an off-the-shelf component with low weight and cost, proven flight history and short delivery schedule. The tank uses a single fill and drain port for both loading and blowdown of fuel. Positive expulsion is maintained by placing the fuel tank off-center from the spacecraft spin axis, allowing centrifugal forces to keep the fuel adjacent to the port at all times after QUATRO spin-up. Two orthogonal thrusters are used. The first thruster, mounted along the spacecraft spin axis but off centered from the center of mass has dual purpose: On continuous thrusting mode it performs the main delta-V maneuvers, after the spacecraft has been positioned to spin along the direction of the required deltaV. On pulsed mode, once per spin, it torques and re-orients the spacecraft to point at any given direction. Since the thruster plume cannot be controlled to better than 0.5 degrees, we deliberately design it to be ~1 degree canted away from the spin axis to spin up the spacecraft during its operation. The second thruster then acts to slow the spin rates induced by the first thruster.

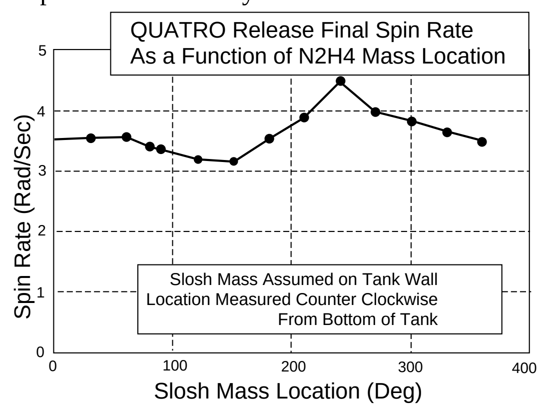

Figure 9. QUATRO simulation results show that a >30 RPM spin rate is achieved independent of initial fuel location.

The stiff DPU casing is both the mounting point of QUATRO on the LV adapter and the mounting of the tank within QUATRO. The rest of the propulsion system, instruments and spacecraft subsystems are mounted on the spacecraft stiff Al plates that connect the honeycomb Al solar panel support. Graphite epoxy shells cover the tank and provide added stiffness, as well as mounting surface for Kapton thermal blankets and two spacecraft antennas. The MAG boom is the only deployable part of the QUATRO spacecraft. It is a graphite epoxy boom (Lunar Prospector heritage) deployed via centrifugal acceleration on a hinge immediately after QUATRO release. It latches in place radially outwards from the spacecraft center of mass.

QUATRO is powered from three 12"X6" GaAs panels, made of 2X2 cm sized cells with 6 mils of coverglass. Each panel produces 6.31 Watts power at 32.54 Volts at end-of-life in the QUATRO radiation environment. A string of 24 NiMH 1.2V battery cells, provides 33.4 Whr at 28.8 V. A second string with its own charger is included for redundancy. RF operation during 12 min. science data downlink can be easily accommodated by a single string. Alternating between the two battery strings from one ground contact to the next provides low battery stress and redundancy. After each downlink the battery string is recharged at 1.75 Watts in 3.5 hrs.

Battery control and conditioning takes place on the main

DPU. Power distribution to Tx/Rx, HVPS, and instruments is taking place at FET-switched 28 Volts. Power down-conversion to 5V for the DPU and A/D converters, and +-12 V for the amplifiers is taking place via InterPoint MCH-series power converters. The DPU centralizes the operation and data collection for all of the instruments/subsystems and minimizes external harnessing. Spacecraft uplink and downlink is accomplished using two body mounted ground-plane antennas, one 1/4 wavelength and the other 3/4 wavelength with a maximum gain of 2.7 dBi. The RF operation is described in detail in Angelopoulos et al. [1998].

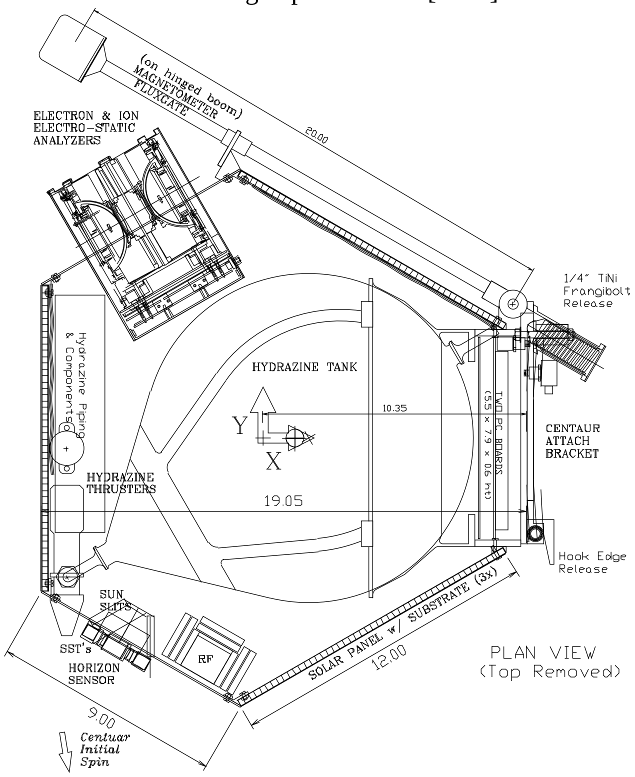

Figure 10. QUATRO spacecraft design.

Thermal control is passive; the tight thermal linkage between spacecraft elements allows a prolonged survival of the spacecraft in shadows (>90 minutes). Heaters are baselined as a backup and are only used during inadvertent shadows that are longer than 90 minutes. Although data downlink during shadows will be avoided as a precautionary measure, heater usage at the inbound or outbound legs is highly unlikely; heater usage is primarily for thermal control backup near apogee, where shadows tend to be the longest. A parametric study of the launch orbital elements, completed by graduate student M. Somoza, indicates that for any launch date, orbital elements that keep the longest shadow of the mission to less than 90 minutes can always be found.

The QUATRO cost and schedule strive to maximize science return while assuring a low risk due to extensive usage of proven technologies. By viewing the entire QUATRO spacecraft as one instrument with central development and management at a single institution, integration and testing can be minimized further. The complexity and development time of the QUATRO spacecraft design is similar to the complexity of a single scientific experiment on a classical space physics satellite. In addition, building four identical spacecraft for a mission that only requires two-spacecraft conjunctions for its basic science goals mitigates risk and abolishes an expensive quality assurance program. Thus, traditional spacecraft cost models cannot approximate the cost of the QUATRO spacecraft estimated from grassroots accounting.

3. CONCLUSIONS

Using funds from CALSPACE grant, the QUATRO spacecraft preliminary design has already been completed. A detailed feasibility study for inclusion of QUATRO as a secondary payload has been conducted by Lockheed Martin under NASA/LeRC funding. QUATRO represents an inexpensive, self-justified, high science return first step towards the realization of the constellation mission.

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4. REFERENCES

Angelopoulos, V. et al., Statistical characteristics of bursty bulk flow events, J. Geophys. Res., 99, 21257, 1994.

Angelopoulos, V. A., The role of impulsive particle acceleration in magnetotail circulation, in Proceedings of the Third International Conference on Substorms, ESA SP-389, 17, 1996.

Angelopoulos, V. et al., Magnetotail flow bursts: association to global magnetospheric circulation, relationship to ionospheric activity and direct evidence for localization, Geophys. Res. Lett., 24, 2271, 1997.

Angelopoulos, V., and H. Spence, Magnetospheric constellation: Past, present, and future, in The Physics of Sun-Earth Plasma and Field Processes, AGU monograph series, Ed. by J. L. Burch, 1998.

Angelopoulos, V. et al., Tracking and mission operations for constellation microspacecraft, in Science closure and enabling technologies for constellation class missions, UC Press, (this volume) 1998.

Gun, Y. L., Mechanical design of a microsatellite, Master's thesis, University of California, Berkeley, May 21, 1998.

Hones, E. W., Jr., The magnetotail: its generation and dissipation. In Physics of Solar Planetary Environments, ed. D. J. Williams, AGU, 558, 1976

Kennel, 1992, The Kiruna conjecture: The strong version, in ICS1 proceedings, ESA SP-335, 599, 1992.

Lui, A. T. Y., Current disruption in the Earth's magnetosphere: Observations and models, J. Geophys. Res., 101, 13067, 1996.

McPherron R. et al., Satellite studies of magnetospheric substorms on Aug 15th, 1968, J. Geophys. Res., 78, 3131, 1973.

Nagai, T., er al., Substorm, tail flows, and plasmoids, Adv. in Space Res., 20, 961, 1997.

Rademacher, J. and K. Leschly, Microspacecraft secondary payload launch capabilities and mission possibilities, 11th AIAA/USU conference on small satellites, SSC97-IX-3, 1997.

Shiokawa, K., et al., High-speed ion flow, substorm current wedge, and multiple Pi 2 pulsations, J. Geophys. Res., 103, 4491, 1998.

Siscoe, G.L. Major outstanding questions and implementation principles of a constellation mission, in Science closure and enabling technologies for constellation class missions, UC Press, (this volume) 1998.

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