EMERALD ADCS SUMMER 1999 DOCUMENTATION

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1 INTRODUCTION

Emerald's Attitude Determination and Control System (ADCS) is responsible for meeting the requirements for the Robust Distributed Space System mission.

A summary of the current ADCS design:

> A passive attitude control system will consist of drag panels controlling attitude in the pitch axis and magnetic attitude control in the roll and yaw axes. Determination will be achieved by a three-axis magnetometer, a Stanford developed ODDSS sun sensor system, and three single axis mems-gyroscopes. The magnetometer will tell us the direction of the magnetic field, and the ODDSS system will give us the direction of the sun. With those two pieces of information we can determine our three-axis attitude. The gyroscopes will give us accurate spin and delta angle information in three axes. The gyroscope information can be used to calculated attitude on the dark side of the planet in place of the ODDSS system, and can be used to average out the ODDSS data to get a more accurate attitude vector. Spacecraft relative position will be controlled by changing the angle of the drag panels. The panels will have at least two positions after the initial release: one with the panels parallel to the velocity vector, and one is with them 30 degrees farther open (see figures 1 and 5 for the open position). Both of these positions offer pitch control.

1.1 STATEMENT OF OBJECTIVE

The Attitude Determination and Control Subsystem is responsible for determining the orientation of the spacecraft and controlling that orientation. ADCS must satisfy any dynamic requirements, i.e. spin rate, and any pointing requirements of the other subsystems. ADCS is also responsible for providing a means for the spacecraft to alter its orbit thereby allowing a first-order relative position control.

The current operations plan is to let the ADS run in phase one until a steady attitude pattern is reached. At that time, it can be turned off and sample an orbit once or twice a day. The ADS will be turned back on full time prior to separation of the S/C, and left on until each separated S/C has achieved a steady attitude pattern. At this time it can be shut down except to sample an orbit once or twice a day. The system will have to run full time for various experiments as well, including the micro colloid thruster and the VLF experiment.

1.2 SUBSYSTEM REQUIREMENTS

All of the following requirements must be met.

1.2.1 POSITION CONTROL REQUIREMENTS

For Formation Flying, the Emerald mission must be able to change the orbit of individual Emerald satellites in a predictable manner.

1.2.2 ATTITUDE CONTROL REQUIREMENTS

1.2.2.1 GPS RECEIVER

Must "see" one GPS satellite for 3 minutes. This roughly translates to a desired spin rate of less than 1 /sec.

1.2.2.2 FORMATION FLYING

Emerald must have the ability to change its orbit. If this is to be done using drag panels, then this translates to a spacecraft that must be 3-axis stabilized.

1.2.2.3 VLF LIGHTNING DETECTION
It is desired that the VLF antennas be oriented perpendicular to nadir.

1.2.3 ATTITUDE DETERMINATION REQUIREMENTS

1.2.3.1 MICRO-COLLOID THRUSTER
Measure spin rates as small as 1 degree/sec or smaller if possible.

1.2.3.2 GPS RECEIVER
Determine if Attitude Control Requirements are met. (Measure spin rate of 1 degree/sec).

1.2.3.3 VLF LIGHTNING DETECTION
Determine the attitude to +/- 5 degrees.

1.3 ACTION ITEMS
- The Attitude/Position Control scheme should be further verified as more S/C and separation data is available.
- The magnets for the passive control system need to be ordered.
- The hysterisis rods need to be sized, if possible, or just ordered using past SSDL sizing.
- The three magnetometers need to be ordered.
- We need to contact the mems-gyro company and see if they will donate, or give a great deal on the gyro.
- The ODDSS circuitry design needs to be completed and parts purchased.
- The magnetometer circuitry design needs to be completed to include connections to provide current for biasing for the different modes.
- Must write a procedure for determining the bias currents for each mode.
- Try to encourage communications to develop a system that will provide more than 120 km crosslink.
- Determine the best locations for the magnets, rods, electronics, magnetometers, and gyro.

2 FUNCTION DESCRIPTION

2.1 ENVIRONMENTAL FORCE ANALYSIS

Extensive analysis was performed to determine the effects of different environmental forces on the Emerald spacecraft. Both the Phase I (Connected) and Phase II (Released) configurations were considered. The forces investigated include aerodynamic pressure, solar pressure, gravity gradient, and magnetics. From these analyses, the following important conclusions were found:

- Solar pressure forces are orders of magnitude smaller than the others and therefore do not need to be considered. ~$2*10^{-7}$ N-m
- Aerodynamic forces provide rotational stability in one axis with the drag panels open as shown in Figure 1. In Figure 1, this axis is the one that starts on the hexagonal face visible on the left and travels through both craft. If the configuration as shown in Figure 2 were to be used, the aerodynamic forces on the drag panels would control the axis starting on an axis traveling through the S/C interface and starting on the left visible face. In the Figure 1 configuration, if the Cg is offset from the Cp (immediately between the two S/C) the aerodynamic pressure will cause the craft to rotate about the vertical axis between the two S/C. ~$4*10^{-5}$ N-m
- Gravity gradient provides a small amount of torque in the phase I configuration, but will provide virtually no torque in the phase II configuration. ~$1*10^{-6}$ N-m
- Magnetic torque can be used to orient the craft in two axis via permanent magnets. The magnitude of this torque is variable depending on the size, shape, and material of the magnet. The magnets should be large enough to overcome any torque present due to Cp vs. Cg position and aerodynamic forces.

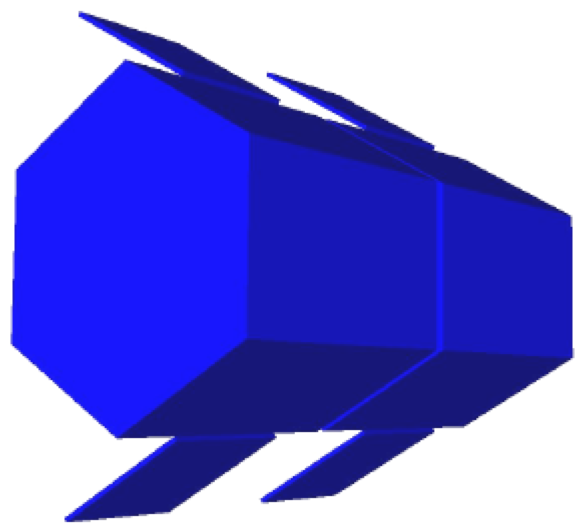

Figure 1: Current Phase I Configuration

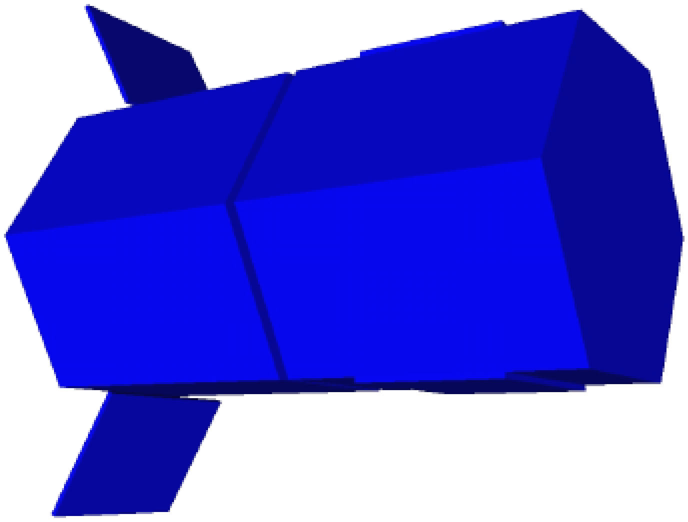

Figure 2: Considered Phase I Configuration

2.2 In-Track vs. Out of Plane Separation Analysis

As the two S/C are released from each other, the springs used to separate them will impart a certain amount of ΔV on each craft. This velocity can be directed in three directions, along the velocity vector (in-track), radially towards and away from nadir, or normal to the orbital plane (out or plane). In the following analyses, a maximum separation velocity of 1m/s is used. This may seem a bit large and the mechanisms team has stated that they can achieve a smaller separation velocity. However, the general trends remain the same.

2.2.1 Radial Separation

A 100% radial separation would be ideal as it provides two orbits that have the same semi-major axis length (therefore the same period) and are just offset. However, the attitude control system (ACS) will not achieve this level of accuracy with magnetic and aerodynamic forces. Imagine the configuration shown in Figure 1 rotated so that one craft is towards nadir and the other is away. To keep the craft in this orientation you could position magnets across the craft pointing towards magnetic north. This magnet would provide control in the Roll and Yaw axis but none in the pitch axis as the magnet can provide no torque about the magnetic field line. The drag panels would only give Yaw authority as discussed in the environmental force section.

In conclusion, without additional massive and power intensive devises such as thrusters or reaction wheels, there is no way to orient the craft for a radial separation

2.2.2 In-Track Separation

This orientation for separation seems desirable because all in plane perturbations can be compensated for using the drag panels to slow down the S/C in the orbit with the larger semi-major axis. However, it is also necessary to see what would happen if the drag panel were to fail.

After an In-Plane separation the S/C would be in approximately the same position with different velocity magnitudes. This would cause the faster craft to be in an orbit with a larger semi-major axis, as shown in Figure 3. (In Figure 3, the solid center orbit represents the Phase I orbit while the two dashed orbits represent the post-separation orbits of the two S/C.) The faster craft would therefore have a longer orbit period time and would come back to the original separation point after the first craft. After one day of orbits the two craft would be separated by 0.6% of an orbit or approximately 250 km. Assuming that the

S/C can communicate with each other a maximum of 120 km, this rate leads to a total of 11.5 hours for any experiment that requires the S/C to communicate with each other.

If the drag panels do work, we assume that the panels on the craft in the larger orbit are immediately opened and that they are closed on the craft in the smaller orbit. The forces that this imposes lead us to 10 days to make the two semi-major axes the same. At this point, the S/C are in offset orbit similar to a radial separation. However, the craft that was in the larger orbit is trailing the other craft. To speed up this craft, the panels are left open for an additional 5 days. These panels are then closed and the panels on the other craft opened. After an additional 5 days, the panels on both craft are put in the same position and the orbits should be equivalent to a radial separation. However, if the S/C are tumbling after separation, the forces on the drag panels could be decreased leading to a longer correction time.

In conclusion, if the craft were separated In-Track and the panels work, it would take a minimum of 20 days to correct the orbits. However, if the panels fail, a large portion of the mission would be over 11.5 hours.

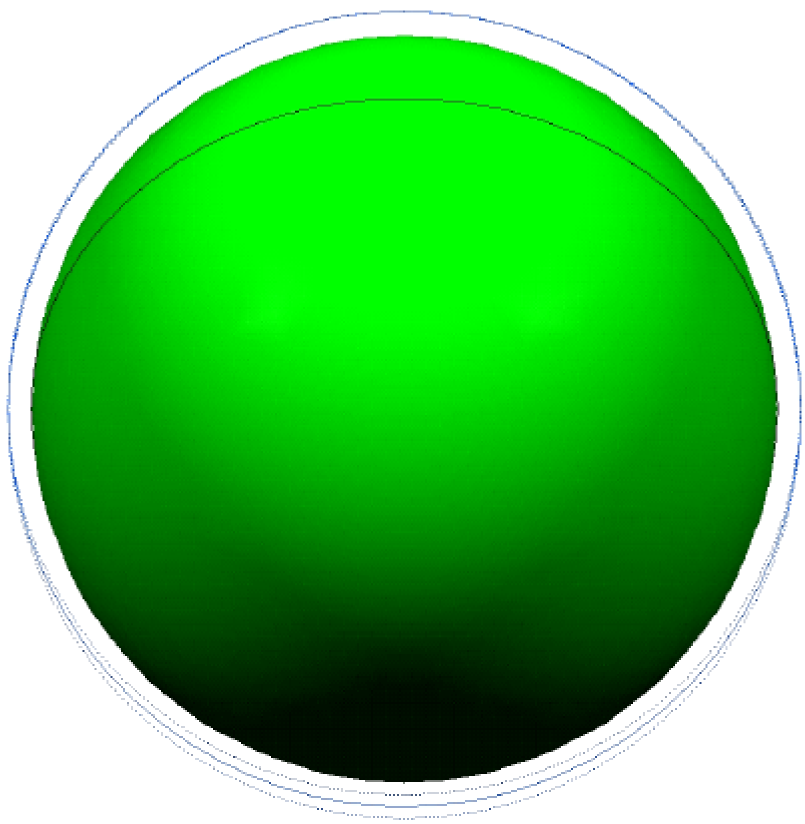

Figure 3: In-Track Separation

2.3 OUT-OF-PLANE SEPARATION

The main concern with Out-of-Plane separation is that it can cause changes in the orbit inclinations. Due to non-spherical Earth J2 perturbations, this difference in inclinations would cause one orbit to precis about the north pole faster than the other, causing a separation of the S/C that cannot be mitigated using drag panels.

As shown in Figure 4, the worst case inclination change occurs when the S/C are separated 100% Out-Of-Plane at the equator. In Figure 4, the solid center orbit represents the Phase I orbit while the two dashed orbits represent the after separation orbits of the two S/C. At first, it can be seen that the S/C will cross paths twice per orbit (at the equator on each side of the planet). The largest separation in the first orbits is 0.822 km at the most northern and southern points in the orbit.

However, this separation causes a 0.0074° change in inclination between the two S/C. The J2 perturbations then lead to a change in the one orbit in relation to the other of 0.0009° per day about the North Pole or approximately 0.1 km/day at the equator. Equivalently, this leads to ~3 km/month or 18 to 36 km for the 6-12 month planned mission.

In conclusion, even the worst case Out-Of-Plane separation leads to a situation where the mission can succeed even if the drag panels experiment does not.

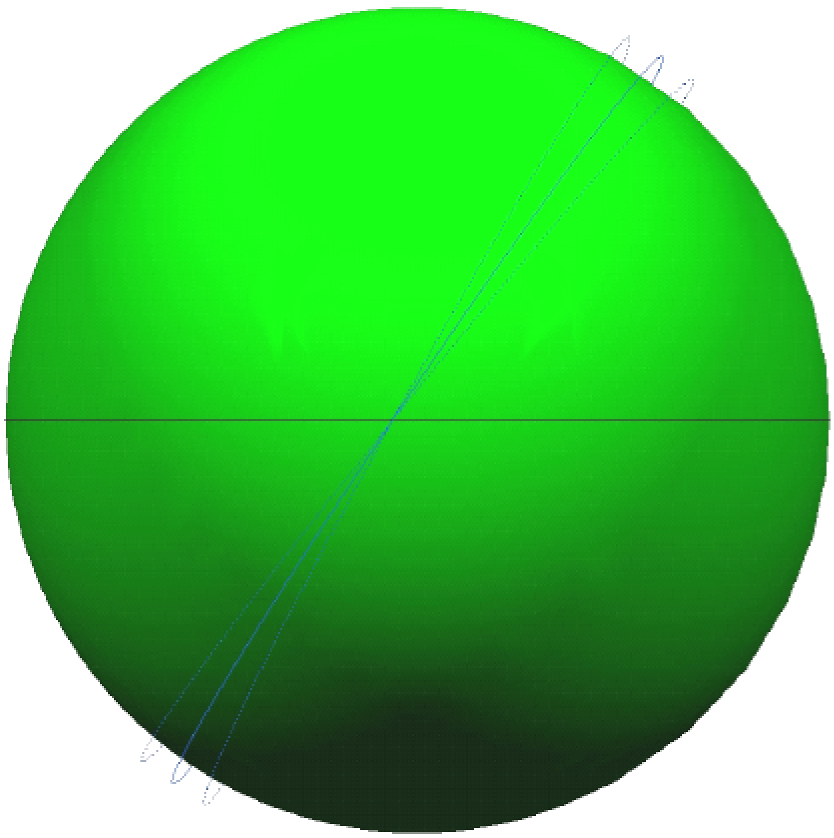

Figure 4: Out-Of-Plane Separation

2.4 IDEAL SEPARATION

As stated before, radial separation would be the best situation. However, this is not possible with magnetic and aerodynamic passive control. Also, it is desirable to reduce the In-Track separation as much as possible and to a lesser degree it is desirable to reduce the Out-Of-Plane inclination change as much as possible.

This leads to the following scenario. As the S/C are orbiting in Phase 1 (see the solid line in Figure 4), the magnetic forces will make them oscillate in a given cone. The idea is to choose a separation time that this oscillation will provide virtually no In-Track velocity change and minimal inclination change. This occurs close to the northernmost and southernmost locations in the orbit. Assume we are talking about the northernmost location. At this location, magnets will want to point at an angle towards the ground and north with no In-Track component. In addition, an Out-Of-Plane separation here would provide far less inclination change than the same separation at the equator. Also, because there is a component of the vector pointing towards nadir, the Out-Of-Plane separation is reduced further reducing the inclination change. More analysis should be done on this before launch, and the analysis should be complete after the S/C is in orbit and the phase I orbit is characterized. However, A separation near the north or south locations is ideal.

2.5 ATTITUDE CONTROL DESIGN

The above arguments lead to the design shown in Figure 5. As shown, the magnets give authority in the roll and yaw directions and will orient the S/C in the direction described in the Ideal Separation section. At the same time, the drag panels will give authority in the pitch axis. The craft is therefore essentially 3-axis stabilized in both the phase I and phase II configurations. Note that neither magnets or drag panels provide damping. Damping will have to be accomplished hysterisis rods.

Also note that this drawing shows the panels at 6.75" in length. This was provided as a minimum length to the Mechanisms Team. Since that time, power has asked that the panels be full-length to accommodate full solar cell strings. Full-length would also supply ACS with more authority. Therefore, full-length panels are the current design.

The magnetic direction is all that is shown here. The magnets can be divided and located anywhere in the S/C provided that their direction is correct.

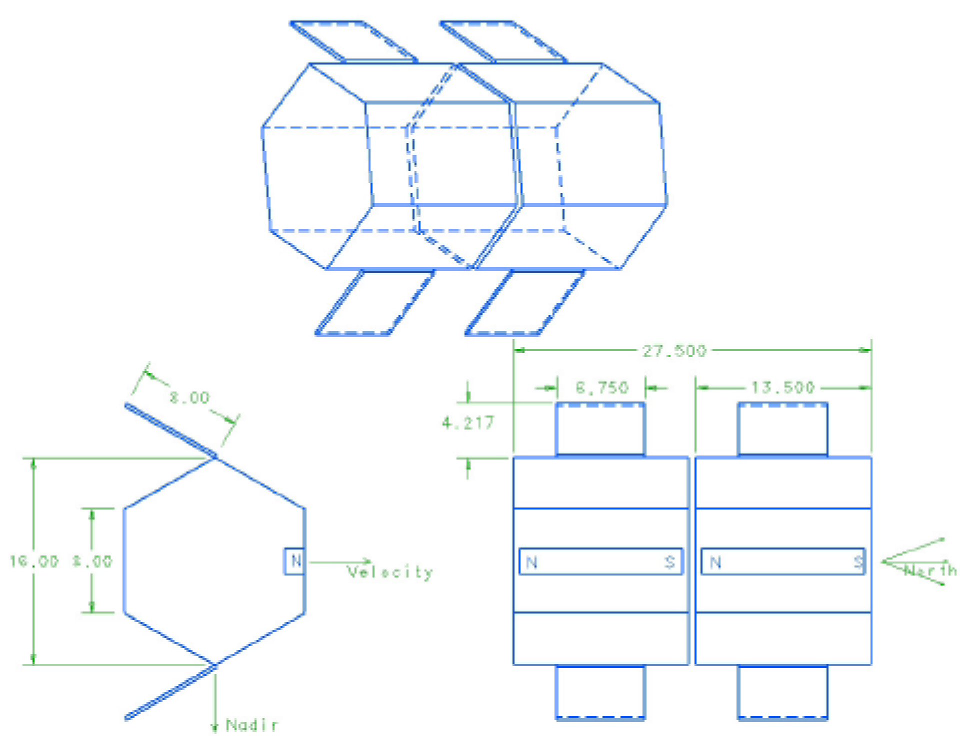

Figure 5: Current ACS Design

3 PASSIVE MAGNETIC CONTROL SYSTEM

The following is an explanation of how the magnets were sized. These calculations were also conducted by a program used at the Dexter Magnet company for sizing magnets and the results came out within 1 percent. First, the expected aerodynamic torque is calculated. Then, the torque available from one magnet at 10 degrees off of the magnetic field line is calculated.

3.1 AERODYNAMIC TORQUE

The following calculation assumes that the distance from the Cp to the Cg is 3 inches in the north-south direction on the craft. Also note the assumptions for the frontal face area, the atmospheric density, the coefficient of drag, and the satellite velocity. It may be advisable to try out different possible cases.

Aerodynamic Torque at 3" Cg vs. Geo. Center

$A := 3 \cdot 8 \cdot 13 \cdot in^2$ $A = 312 \cdot in^2$ Front Face for Aerodynamics

$d := 3 \cdot in$ Distance from Cg to Cp

$\rho_m := 2.2 \cdot 10^{-11} \cdot \frac{kg}{m^3}$ Atmospheric Density

$C_d := 2.0$ Coefficient of Drag

$Ve := 10.25 \cdot \frac{km}{sec}$ Satellite Velocity

$F := \frac{1}{2} \cdot \rho_m \cdot C_d \cdot A \cdot Ve^2$ $F = 4.653 \cdot 10^{-4} \cdot newton$ Aerodynamic Force

$T := F \cdot d$ $T = 3.545 \cdot 10^{-5} \cdot newton \cdot m$ Aerodynamic Torque

3.2 MAGNETIC TORQUE

The following calculation assume that we are using the magnetic material Neodymium Iron Boron 48. This is a new high performance material from Dexter. It outperforms Alnico magnets which have been previously used at SSDL. The properties used for the magnet are from the company and are hand recorded on a sticky in our copy of their manual. The geometry of this example magnet was chosen because it fits into emerald without having to cut through the levels and Dexter has it in stock as an off the shelf component. Note that it is assumed the magnet is 10 degrees from the magnetic field lines.

Torque Calculation Using Neodymium Iron Boron 48

$B_R := .4 \cdot gauss$ — Earth's Magnetic Field (approximate)

$B_r := 1.35 \cdot tesla$ $\quad B_r = 1.35 \cdot 10^4 \cdot gauss$ — Magnetic Material Residual Inductance

$D := .25 \cdot in$ — Diameter of Solid Magnet

$L := 4 \cdot in$ — Length of Solid Magnet

$V := \pi \cdot \left(\frac{D}{2}\right)^2 \cdot L$ — Volume of Solid Magnet

$\rho := .27 \cdot \frac{lb}{in^3}$ $\quad \rho = 7.474 \cdot \frac{gm}{cm^3}$ — Mass Density of Solid Magnet

$\theta := 10 \cdot deg$ — Angle of Magnet to Earth's Field

$\mu_0 := 4 \cdot \pi \cdot 10^{-7} \cdot \frac{newton \cdot sec^2}{coul^2}$ — Magnetic Permeability of Air

$dm := \frac{B_r \cdot V}{\mu_0}$ $\quad dm = 3.457 \cdot amp \cdot m^2$ — Permanent Magnet's Dipole Moment

$T := dm \cdot B_R \cdot \sin(\theta)$ $\quad T = 2.401 \cdot 10^{-5} \cdot newton \cdot m$ — Torque Induced on Permanent Magnet

$Mass := V \cdot \rho$ $\quad Mass = 24.047 \cdot gm$ — Mass of Permanent Magnet

$\frac{T}{Mass} = 9.984 \cdot 10^{-4} \cdot m^2 \cdot sec^{-2}$ — Torque to Mass Ratio

3.3 MAGNET SIZING

From the above calculations, it can be seen that two of these 4”X0.25”, 24 gm magnets could handle the expected aerodynamic torque with a 35% margin. However, just in case our Cg is more than 3 inches off of the Cp and to give additional authority against aerodynamic torque, 4 magnets will be used. With 4 of these magnets the Cg could be 8” away from the Cp (which happens to be outside of the S/C), and the magnets would still overpower the aerodynamic torque once the magnets are at 10 degrees from the field lines.

4 ATTITUDE DETERMINATION SYSTEM

There is no active attitude control on the S/C and no subsystem or experiment needs attitude information at the S/C level. Therefore, it was decided to not process the magnetometer data, ODDSS data, or the gyro data on board. The data will be transferred at the ground and post processed there. This is beneficial in that it doesn't require addition CPU time on the craft or any external memory. Also, no orbit data will have to be uplinked to the S/C. Instead of uplinked orbit information, a lot of processing on board, and a downlink of the attitude, there is simply a downlink of data. This data will be processed on the ground where there are relatively unlimited computing and power resources.

Figure 6 shows the electronic connections as defined up to this time.

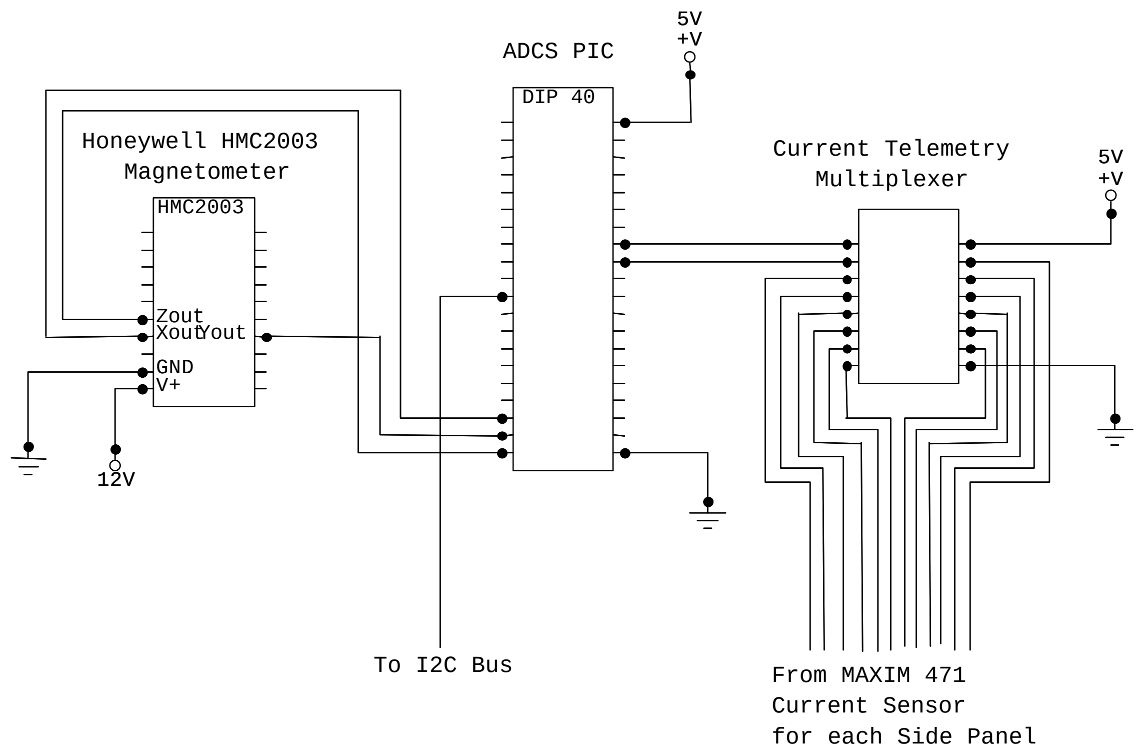

Figure 6: Current ADS Design

4.1 SUBSYSTEM INTERFACING

The magnetometer, gyros (not shown), and ODDSS system will interface to the I^2C bus by utilizing the PIC 16C74's built in I^2C capabilities. All data transfer will occur via the I^2C bus. A command dictionary will be defined for the magnetometer subsystem. The CPU or other subsystem will utilize these commands to request data from the magnetometer subsystem.

4.2 FUNCTIONAL DESCRIPTION

The magnetometer is capable of measuring the earth's magnetic field and outputting a voltage based on the field strength intensity along any of the three primary axes of the spacecraft. This data is converted to digital data via the on-board analog to digital converter provided by the PIC microprocessor. This data can be stored onto dedicated subsystem RAM or fed directly to the CPU or other subsystem. The data is logged and time stamped. The time stamped data is combined with orbital position information to determine absolute attitude of the spacecraft by an estimation algorithm.

The gyroscopes are capable of measuring the spin rate of the S/C and outputting a voltage. This voltage is converted to digital, time stamped, and stored in the same manor as the magnetometer data.

ODDSS simply uses the solar array current data that is already being measured to calculate the position of the sun. Two leads are run from the power system multiplexer to the ADCS PIC, converted to digital, time stamped and stored.

4.3 COMPONENT SELECTION

The Honeywell HMC2003 three axis magnetic sensor hybrid has been selected as the magnetometer. This selection is based on its low cost, high sensitivity, three axis ability, and previous research by SSDL's Orion project. This device uses a 6 to 15V supply voltage. Detailed documentation on this device is available in the ADCS subsystem file.

The Analog Devices ADRS60 ±60deg/s Single Chip Rate Gyro with Signal Conditioning has been selected as the gyroscopes. This device measures 0.4 X 0.3 X 0.2 inches and can measure up to ±60 deg/s very accurately. The devise uses a 5 V supply voltage and a 5 mA current. Detailed specifications of this devise are available in the ADCS subsystem file.

The ODDSS system requires no additional components.

4.4 ADCS BUDGETS

The following table shows the current ADCS Budgets.

	Mass (gm)	Volume (in)	Power (w)	Data (high)	Data (low)
Electronics	200	4X6X2	0.240	5 byte/sec*	10 byte/min*
Magnetometer	10		0.240	3 byte/sec	6 byte/min
ODDSS	15	Included	0.000	3 byte/sec	6 byte/min
Gyroscope	50	Above	0.025	3 byte/sec	6 byte/min
PIC	50		0.125	2 byte/sec	4 byte/min
Magnets (4)	150	.25od X 4	0	0	0
Hysteresis Rods (6)	150	.14x.14x7	0	0	0
Margin (20%)	100		0.126	1 byte/sec	2 byte/min
TOTAL	600		0.756	6 byte/sec*	12 byte/min*