AEROSPACE REPORT NO.
ATR-2011(5389)-2

# Reaction Wheel Supplier Survey

January 31, 2011

Luke A. Rinard[1], Erin L. Chapman[1], and Stephen C. Ringler[2]

[1]Electromechanical Control Department, Vehicle Systems Division
[2]Program Development, NASA Programs Division

Prepared for:

NASA Marshall Space Flight Center's Chief Engineer Office
National Space Science and Technology Center
320 Sparkman Drive
Huntsville, AL 35805

Contract No. NNM07AA96C

Authorized by: Civil and Commercial Operations

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## Abstract

NASA's Discovery, New Frontiers and Lunar Quest Program Office contracted with The Aerospace Corporation to perform a survey of reaction wheel suppliers. The results of the survey are intended to be used to assist in procurement of reaction wheels for Discovery, New Frontiers and Lunar Quest missions. Aerospace gathered reaction wheel vendor and product information from non-sensitive internal resources, the internet, and communications with vendors. The information gathered includes: general information on each reaction wheel vendor and a listing of the available reaction wheel models along with performance capabilities, specifications, and flight history. Historical Attitude Determination and Control Subsystem (ADCS) cost and schedule performance were analyzed and evaluated with respect to reaction wheel procurements.

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# 1. Abstract

NASA's Discovery, New Frontiers and Lunar Quest Program Office contracted with The Aerospace Corporation to perform a survey of reaction wheel suppliers. The results of the survey are intended to be used to assist in procurement of reaction wheels for Discovery, New Frontiers and Lunar Quest missions. Aerospace gathered reaction wheel vendor and product information from non-sensitive internal resources, the internet, and communications with vendors. The information gathered includes: general information on each reaction wheel vendor and a listing of the available reaction wheel models along with performance capabilities, specifications, and flight history. Historical Attitude Determination and Control Subsystem (ADCS) cost and schedule performance were analyzed and evaluated with respect to reaction wheel procurements.

## 2. Reaction Wheel Overview

Reaction wheels are used for active stabilization and control of a spacecraft. They require the use of spacecraft power and electrical commands, but do not require propellant. Figure 1 shows a cross sectional view of a typical reaction wheel assembly (RWA), showing its various working parts, which include bearings, a rotor, a motor, and control and power electronics. On the axis of the RWA's motor is an inertia rotor, or flywheel. The flywheel changes speed to absorb angular momentum imparted on the spacecraft from external torques. Examples of external torques include atmospheric drag and solar pressure.

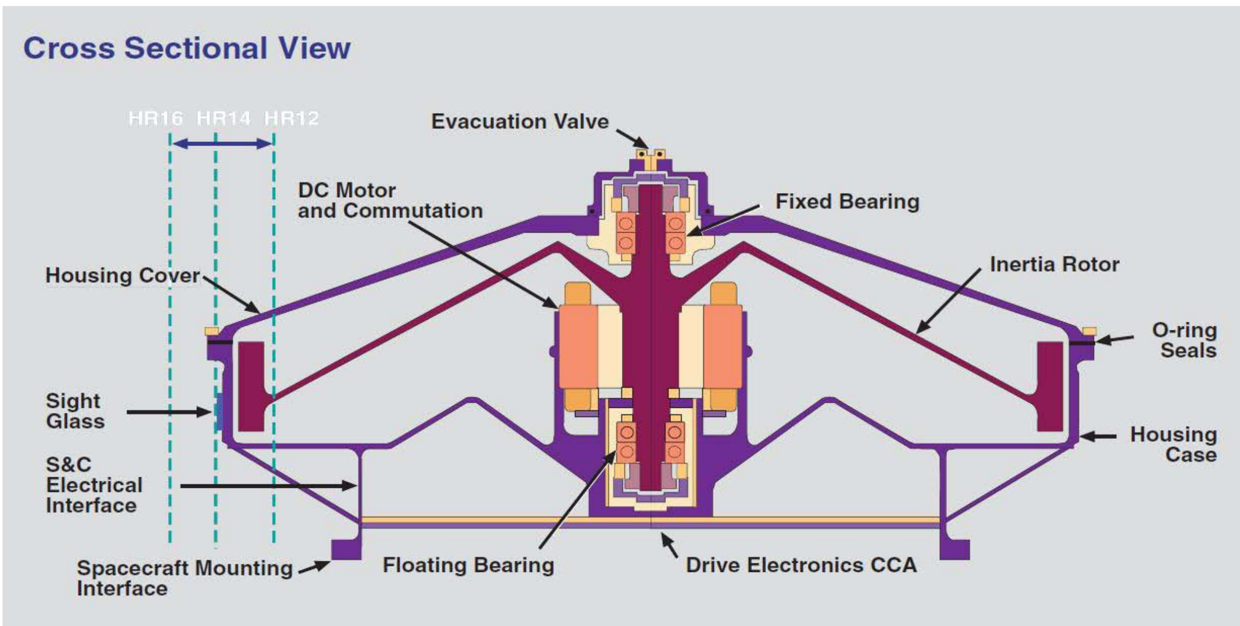


Figure 1. Honeywell Constellation Series Cross Section (Image courtesy of Honeywell International).

### 2.1 Bearings

The bearings on an RWA allow constrained relative motion between the rotor and motor. Bearings (Figure 2) consist of an external and internal race, rolling elements (balls or rollers), and a separator/cage. The external race is a ring with an inside groove in which the balls roll and slide. The inner race is a ring with an external groove in which these same balls roll and slide. The separator or cage is a ring with a number of holes or pockets equal to the number of balls in the bearing. The holes are slightly larger in diameter than the balls to accommodate free rolling by keeping the balls from contacting each other. Some bearings have built-in shields to prevent contaminants from entering the races, but this is not typically done for RWAs.

Bearings are designed to operate with lubricant between the rolling elements and races to produce a hydrodynamic effect that keeps these pieces separated by a film barrier. This prevents metal-to-metal contact that could damage the rolling elements. It is important to note that speed is a factor in maintaining the hydrodynamic effect. Slow speed can result in no lift off and metal-to-metal contact.

There are bearings that operate in this regime, which is referred to as “boundary lubrication,” but this is not conducive to long life.

Figure 2. Typical Ball Bearing (Image courtesy of Wikimedia Commons).

## 2.2 Motor

One of the most common types of motors used in RWAs is the brushless DC (BLDC) motor. BLDC motors are composed of a rotating portion called the rotor, on which permanent magnets are mounted, and a stationary part, called the stator, that houses the windings. Running current through the stator windings creates a magnetic field that can be rotated to pull the rotor in either direction at a wide range of speeds. Typically, BLDC motors have two or three sets of windings evenly spaced around the rotor (referred to as 2-phase and 3-phase motors, respectively). For redundancy, additional sets of windings can be included.


Figure 3. Stator of a Two-Phase BLDC Motor. (Image courtesy of Wikimedia Commons).

## 2.3 Electronics

RWA electronics include all of the control electronics, power elements, and harnesses. Common RWA electronics components consist of wheel speed sensors, motor current sensors, motor speed controllers, bus interface components and harnesses. Different RWA configurations have electronics enclosed in the rotor housing or in a separate enclosure. Also, the electronics can have any combination of analog or digital interfaces depending on the satellite's configuration. Electronics that are inside the evacuated wheel housing have been shown to exhibit outgassing that can raise the housing internal pressure to levels that are unacceptable.

Figure 4. Reaction Wheel Electronics (Image courtesy of Surrey Satellite Technology).

# 3. Vendor Information

This section includes general information about each reaction wheel vendor in the survey as well as a table of wheel specifications. Table 1 lists the vendors included in the survey.

Table 1. Reaction Wheel Vendors

| Domestic | International |
|---|---|
| Goodrich Corporation | Bradford Engineering |
| Honeywell International | Microsat Systems Canada Inc. |
| L-3 Communications | Rockwell Collins |
| Maryland Aerospace Inc. | Surrey Satellite Technology Ltd. |

A complete specifications table that includes all wheels from all vendors can be found in the appendix. Specifications for 77 wheels are captured. Data was collected on an additional 55 models that were unable to be validated and not included in database.

## 3.1 Goodrich Corporation

### 3.1.1 General Comments

The current Goodrich product line consists of the Torquewheel series of reaction wheels. Within this series there are 5 different types: AA, A, B, C, and E (Figure 5). These wheels share common components and have similar structure. The primary difference is the diameter and mass of the rotors, which determines momentum capability. Torquewheels range from 1-45 Nms momentum capacity, 6-400 mNm torque, and 1,000-10,000 RPM wheel speed. The designator for the Torquewheel series is TW-1AA8, where “TW” stands for Torquewheel, the first number is the momentum capacity in NMS, the letters indicate reaction wheel housing size, and the last number is the reaction torque in milli-Nm. Specifications for Goodrich’s wheels are listed in Table 2. Goodrich has delivered over four hundred reaction wheels to date. The general designs have been evolving for years, tracing their heritage to a scanning momentum wheel developed in the 1980s that combined an Earth sensor and reaction wheel in a single package [1]. The Goodrich reaction wheels progressed from short term experimental missions and Shuttle Get Away specials, to commercial missions, then to NASA science missions, and most recently to DOD missions (C/NOFS, AEHF, GPS IIF, SBSS) [2].

Goodrich was originally Ithaco Space Systems. Goodrich Intelligence, Surveillance, and Reconnaissance (ISR) Systems acquired Ithaco in 1999. Goodrich ISR continues to manufacture their reaction wheels in Ithaca, New York [3].

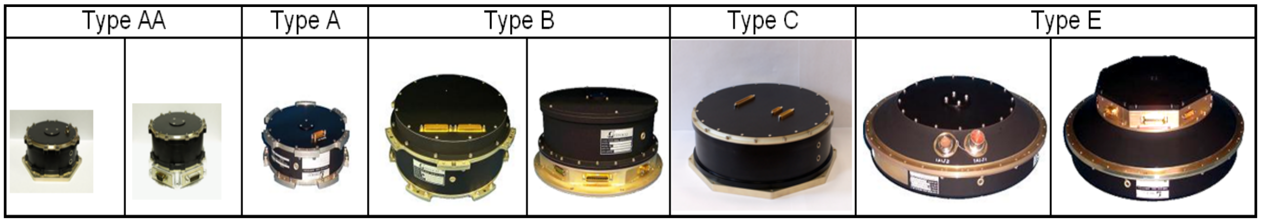


Figure 5. Goodrich's Torquewheel Series Reaction Wheels (Image Courtesy of Goodrich Corporation)

### 3.1.2 Contact Information

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### 3.1.3 Specifications

Table 2a. Goodrich Reaction Wheel Specifications [2]

| Model | TW-1AA8 | TW-1.5AA6 | TW-1AA8 | TW-1.5AA6 |
|---|---|---|---|---|
| Mass (kg) | 1.6 | 1.6 | 1.3 | 1.3 |
| Peak Power (W) | 14 | 18 | 13 | 18 |
| Average Power (W) | 4 | 4 | 4 | 4 |
| Bus Voltage (V) | 28 to 70 | 28 to 70 | 28 to 70 | 28 to 70 |
| Momentum (Nms) | 1 | 1.5 | 1 | 1.5 |
| Output Torque (Nm) | 0.008 | 0.006 | 0.008 | 0.006 |
| Wheel Speed (RPM) | 6500 | 10000 | 6500 | 10000 |
| Vibration (g-rms) | N/A | N/A | N/A | N/A |
| Low Temp (C) | N/A | N/A | N/A | N/A |
| High Temp (C) | N/A | N/A | N/A | N/A |
| Dimensions (cm) | 13.8 dia x 8.3 | 13.8 dia x 8.3 | 13.8 dia x 7 | 13.8 dia x 7 |
| Electronics Included | Yes | Yes | No | No |
| Electronics Mass (kg -- if not included) | N/A | N/A | 1, 1.5, 2.1, 3 (for 1, 2, 3 or 4 wheels) | 1, 1.5, 2.1, 3 (for 1, 2, 3 or 4 wheels) |
| Electronics Dimensions (cm) | N/A | N/A | 16 x19 x3.8n (n = number of RW) | 16 x19 x3.8n (n = number of RW) |
| Missions/Built for Flight | New Product | New Product | New Product | New Product |
| Comments | Electronics Included | Electronics Included | Electronics Separate | Electronics Separate |

Table 2b. Goodrich Reaction Wheel Specifications [2]

| Model | TW-4A12 | TW-2A40 | TW-16B32 | TW-8B90 |
|---|---|---|---|---|
| Mass (kg) | 2.55 | 2.55 | 6 | 6 |
| Peak Power (W) | 25 | 25 | 50 | 55 |
| Average Power (W) | 5 | 5 | 7 | 7 |
| Bus Voltage (V) | 28 to 70 | 28 to 70 | 28 to 70 | 28 to 70 |
| Momentum (Nms) | 4 | 2 | 16.5 | 8 |
| Output Torque (Nm) | 0.012 | 0.04 | 0.032 | 0.09 |
| Wheel Speed (RPM) | 5100 | 2550 | 5100 | 2500 |
| Vibration (g-rms) | N/A | N/A | N/A | N/A |
| Low Temp (C) | N/A | N/A | N/A | N/A |
| High Temp (C) | N/A | N/A | N/A | N/A |
| Dimensions (cm) | 20.5 dia x 6.4 | 20.5 dia x 6.4 | 25.5 dia x 12.4 | 25.5 dia x 12.4 |
| Electronics Included | No | No | Yes | Yes |
| Electronics Mass (kg -- if not included) | 1, 1.5, 2.1, 3 (for 1, 2, 3 or 4 wheels) | 1, 1.5, 2.1, 3 (for 1, 2, 3 or 4 wheels) | N/A | N/A |
| Electronics Dimensions (cm) | 16 x19 x3.8n (n = number of RW) | 16 x19 x3.8n (n = number of RW) | N/A | N/A |
| Missions/Built for Flight | LEO, GEO, and Interplanetary missions | LEO, GEO, and Interplanetary missions | LEO, Heliocentric, and Interplanetary missions | LEO, Heliocentric, and Interplanetary missions |
| Comments | Electronics Separate | Electronics Separate | | |

Table 2c. Goodrich Reaction Wheel Specifications [2]

| Model | TW-4B200 | TW-16B200 | TW-8B400 | TW-45C250 |
|---|---|---|---|---|
| Mass (kg) | 6 | 7.5 | 7.5 | 12 |
| Peak Power (W) | 70 | 250 | 250 | 250 |
| Average Power (W) | 7 | 15 | 15 | 10 |
| Bus Voltage (V) | 28 to 70 | 28 to 70 | 28 to 70 | 28 to 70 |
| Momentum (Nms) | 4 | 16.5 | 8 | 45 |
| Output Torque (Nm) | 0.2 | 0.2 | 0.4 | 0.25 |
| Wheel Speed (RPM) | 1235 | 5100 | 2510 | 4500 |
| Vibration (g-rms) | N/A | N/A | N/A | N/A |
| Low Temp (C) | N/A | N/A | N/A | N/A |
| High Temp (C) | N/A | N/A | N/A | N/A |
| Dimensions (cm) | 25.5 dia x 12.4 | 28.0 dia x 13.5 | 28.0 dia x 13.5 | 30.5 dia x 11.5 |
| Electronics Included | Yes | Yes | Yes | Yes |
| Missions/Built for Flight | LEO, Heliocentric, and Interplanetary missions | LEO, MEO, and GEO missions | LEO, MEO, and GEO missions | New Product |

Table 2d. Goodrich Reaction Wheel Specifications [2]

| Model | TW-35C600 | TW-50E300 | TW-26E700 | TW-50E180 |
|---|---|---|---|---|
| Mass (kg) | 12 | 10.4 | 10.4 | 12.4 |
| Peak Power (W) | 400 | 300 | 380 | 250 |
| Average Power (W) | 10 | 22 | 22 | 22 |
| Bus Voltage (V) | 28 to 70 | 28 to 70 | 28 to 70 | 28 to 70 |
| Momentum (Nms) | 35 | 50 | 26 | 50 |
| Output Torque (Nm) | 0.6 | 0.3 | 0.7 | 0.18 |
| Wheel Speed (RPM) | 3500 | 3900 | 2020 | 3900 |
| Vibration (g-rms) | N/A | N/A | N/A | N/A |
| Low Temp (C) | N/A | N/A | N/A | N/A |
| High Temp (C) | N/A | N/A | N/A | N/A |
| Dimensions (cm) | 30.5 dia x 11.5 | 39.4 dia x 16.6 | 39.4 dia x 16.6 | 39.4 dia x 18 |
| Electronics Included | Yes | No | No | Yes |
| Electronics Mass (kg -- if not included) | N/A | 4.1 | 4.1 | N/A |
| Electronics Dimensions (cm) | N/A | 18 x 18 x 9 | 18 x 18 x 9 | N/A |
| Missions/Built for Flight | New Product | LEO, L-2, and GEO missions | LEO, L-2, and GEO missions | LEO missions |

Table 2e. Goodrich Reaction Wheel Specifications [2]

| Model | TW-26E400 | TW-13E1000 | TW-22E2000 |
|---|---|---|---|
| Mass (kg) | 12.4 | 12.4 | 24 |
| Peak Power (W) | 250 | 300 | 300 |
| Average Power (W) | 22 | 22 | N/A |
| Bus Voltage (V) | 28 to 70 | 28 to 70 | 28 to 70 |
| Momentum (Nms) | 26 | 13 | 22.5 |
| Output Torque (Nm) | 0.4 | 1 | 2 |
| Wheel Speed (RPM) | 2020 | 1000 | 550 |
| Vibration (g-rms) | N/A | N/A | N/A |
| Low Temp (C) | N/A | N/A | N/A |
| High Temp (C) | N/A | N/A | N/A |
| Dimensions (cm) | 39.4 dia x 18 | 39.4 dia x 18 | 39.4 dia x 18 |
| Electronics Included | Yes | Yes | Yes |
| Missions/Built for Flight | LEO missions | LEO missions | LEO missions |

### 3.2 Honeywell International

#### 3.2.1 General Comments

The current Honeywell International (HI) product line consists of the Constellation series of reaction wheels and the HR0610 reaction wheel for small spacecraft. These wheels share common components and have similar structure. The primary difference is the diameter and mass of the rotors, which determines momentum capability. The designator for the Constellation series is HR-rs-mtm, where rs is rotor size and mtm is momentum capability. HI's wheels range from 4 to 100 Nms momentum capacity, 55 to 400 mNm torque. All Honeywell's wheels have a top speed of 6,000 RPM. Specifications for HI's wheels are listed in Table 3. The general designs have been evolving for many years, tracing their heritage to Fleetsatcom momentum wheels developed in the 1960s. The reaction wheels have also been influenced by Honeywell's control moment gyroscope (CMG) experience, particularly with regard to bearings, mechanisms, and lubricants, as the CMG application is more demanding [4] [5].

Honeywell's reaction wheels are manufactured by Honeywell Aerospace in Glendale, Arizona.

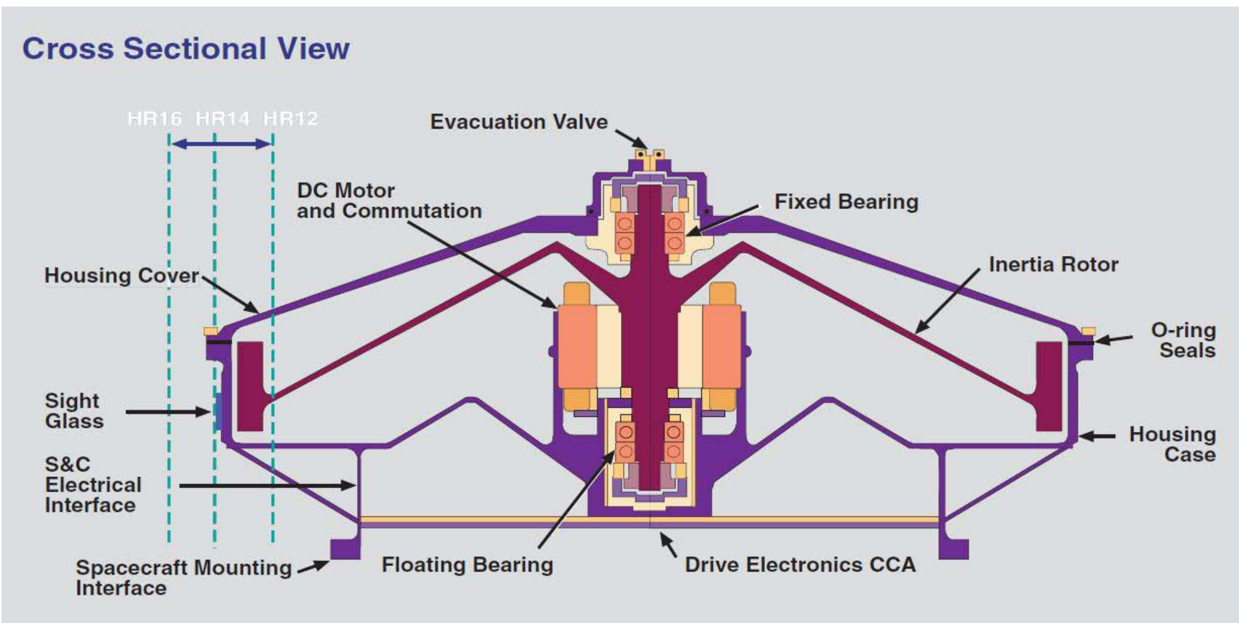


Figure 6. Honeywell Constellation Series Cross Section (Image courtesy of Honeywell International)

#### 3.2.2 Contact Information

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### 3.2.3 Specifications

Table 3a. Honeywell Reaction Wheel Specifications
[4][5]

| Model | HR-12-12 | HR-12-25 | HR-12-50 | HR-14-25 | HR-14-50 |
|---|---|---|---|---|---|
| Mass (kg) | 6 | 7 | 9.5 | 7.5 | 8.5 |
| Peak Power (W) | 195 | 195 | 195 | 195 | 195 |
| Bus Voltage (V) | 14 to 80 | 15 to 80 | 16 to 80 | 17 to 80 | 18 to 80 |
| Momentum (Nms) | 12 | 25 | 50 | 25 | 50 |
| Output Torque (Nm) | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Wheel Speed (RPM) | 6000 | 6000 | 6000 | 6000 | 6000 |
| Vibration (g-rms) | 13.8 | 13.8 | 13.8 | 13.8 | 13.8 |
| Low Temp (C) | -30 | -30 | -30 | -30 | -30 |
| High Temp (C) | 70 | 70 | 70 | 70 | 70 |
| Dimensions (cm) | 31.6 dia X 15.9 (31.6 dia x 14.8 w/o electronics) | 31.6 dia X 15.9 (31.6 dia x 14.8 w/o electronics) | 31.6 dia X 15.9 (31.6 dia x 14.8 w/o electronics) | 36.6 dia X 15.9 (36.6 dia x 14.8 w/o electronics) | 36.6 dia X 15.9 (36.6 dia x 14.8 w/o electronics) |
| Electronics Included | Optional | Optional | Optional | Optional | Optional |
| Electronics Dimensions (cm) | 6 x 16.9 x 23 | 6 x 16.9 x 23 | 6 x 16.9 x 23 | 6 x 16.9 x 23 | 6 x 16.9 x 23 |
| Missions/Built for Flight | Many | Many | Many | Many | Many |
| Radiation (Krad) | 300 | 300 | 300 | 300 | 300 |
| Operational Life (years) | 15 | 15 | 15 | 15 | 15 |
| Comments | Option for integrated electronics or separate unit, also 18 and 37.5 Nms designs available | Option for integrated electronics or separate unit, also 18 and 37.5 Nms designs available | Option for integrated electronics or separate unit, also 18 and 37.5 Nms designs available | Option for integrated electronics or separate unit | Option for integrated electronics or separate unit |

Table 3b. Honeywell Reaction Wheel Specifications
[4][5]

| Model | HR-14-75 | HR-16-50 | HR-16-75 | HR-16-100 | HR0610 |
|---|---|---|---|---|---|
| Mass (kg) | 10.6 | 9 | 10.4 | 12 | 3.6 to 5.0 |
| Peak Power (W) | 195 | 195 | 195 | 195 | 80 |
| Bus Voltage (V) | 19 to 80 | 20 to 80 | 21 to 80 | 22 to 80 | 14 to 23 |
| Momentum (Nms) | 75 | 50 | 75 | 100 | 4 to 12 |
| Output Torque (Nm) | 0.4 | 0.4 | 0.4 | 0.4 | 0.055 |
| Wheel Speed (RPM) | 6000 | 6000 | 6000 | 6000 | 6000 |
| Vibration (g-rms) | 13.8 | 13.8 | 13.8 | 13.8 | 19.8 |
| Low Temp (C) | -30 | -30 | -30 | -30 | -15 |
| High Temp (C) | 70 | 70 | 70 | 70 | 60 |
| Dimensions (cm) | 36.6 dia X 15.9 (36.6 dia x 14.8 w/o electronics) | 41.8 dia X 17.8 (41.8 dia x 15.2 w/o electronics) | 41.8 dia X 17.8 (41.8 dia x 15.2 w/o electronics) | 41.8 dia X 17.8 (41.8 dia x 15.2 w/o electronics) | 26.7 diam X 12 H |
| Electronics Included | Optional | Optional | Optional | Optional | Yes |
| Electronics Dimensions (cm) | 6 x 16.9 x 23 | 6 x 16.9 x 23 | 6 x 16.9 x 23 | 6 x 16.9 x 23 | N/A |
| Missions/Built for Flight | Many | Many | Many | Many | Globstar |
| Radiation (Krad) | 300 | 300 | 300 | 300 | |
| Operational Life (years) | 15 | 15 | 15 | 15 | S equiv, 10 yr life |
| Comments | Option for integrated electronics or separate unit | Option for integrated electronics or separate unit, also 68, 125, and 150 Nms designs | Option for integrated electronics or separate unit, also 68, 125, and 150 Nms designs | Option for integrated electronics or separate unit, also 68, 125, and 150 Nms designs | Modular momentum sizing, 296 RWAs produced which currently supports 56 satellites active on orbit |

### 3.3 L-3 Communications

#### 3.3.1 General Comments

L-3's current product line consists of two models: the RWA-15 High Torque Reaction Wheel and the MWA-50 Low Cost Momentum Wheel Assembly. Both have proven 7 year operational life spans. The RWA-15 has 20 Nms momentum capacity, 0.68 Nm torque and 2200 RPM top speed. The MWA-50 has 67.8 Nms momentum capacity, 0.07 Nm torque and 6600 RPM top speed. They advertise the capability to manufacture custom designs with momentum capacities ranging from 5 to 160 Nms and torque of up to 0.75 Nm. Specifications for L-3's wheels are listed in Table 4. L-3 has delivered hundreds of RWA-15s and MWA-50s which have accumulated over 9,000,000 hours in space. RWA-15s have been used on missions such as IKONOS, LEO, QUICKBIRD, SWIFT, and QSCAT. MWA-50s have been used on IRIDIUM satellites and Indostar. L-3 also provided the control moment gyros to the International Space Station [6].

L-3 Communications' Space and Navigation Division manufactures their reaction wheel line in Budd Lake, New Jersey. L-3 Space and Navigation was originally the Bendix Corporation. Bendix was acquired by Allied Corporation in 1983. In 1985 Allied merged with Signal Companies, Inc. to form AlliedSignal. In 1999, AlliedSignal acquired Honeywell, and the Space and Navigation business was sold to L-3 Communications in response to a Department of Justice mandate [7].

Figure 7. L-3 Communications MWA-50 Momentum Wheel Assembly (Image courtesy of L-3 Communications)

### 3.3.2 Contact Information

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Web: www.l-3com.com/spacenav

### 3.3.3 Specifications

Table 4. L-3 Communications Reaction Wheel Specifications [8][9]

| Model | MWA-50 | RWA-15 |
|---|---|---|
| Mass (kg) | 10.5 | 14 |
| Peak Power (W) | 100 | 230 |
| Bus Voltage (V) | 28 +/- 6 | 28 +/- 6 |
| Momentum (Nms) | 67.8 | 20 |
| Output Torque (Nm) | 0.07 | 0.68 |
| Wheel Speed (RPM) | 6600 | 2200 |
| Dimensions (cm) | 38.6 dia X 14.2 | 36.9 dia x 15.3 |
| Electronics Included | Yes | Yes |
| Missions/Built for Flight | IRIDIUM and Indostar | IKONOS, QSCAT, QBIRD, Swift, LEO |
| Radiation (Krad) | | 30 |
| Operational Life (years) | | 7 |
| Comments | Analog interface | Analog interface |

### 3.4 Maryland Aerospace, Inc.

#### 3.4.1 General Comments

Maryland Aerospace Inc. (MAI) manufactures miniature reaction wheels suitable for micro and nano-satellites up to 50 lb. MAI offers two models of 3-axis reaction wheels: the MAI-101 and the MAI-201. The MAI-101 is the smaller of the two and is appropriate for spacecraft up to 20 lb. The MAI-201 is larger and appropriate for spacecraft up to 50 lb. The MAI-101 has 0.002 Nms momentum capacity, 0.635 mNm torque, and 10,000 RPM top speed. The MAI-201 has 0.02 Nms momentum capacity, 5 mNm torque and 10,000 RPM top speed. MAI also manufactures complete 3-axis attitude determination and control systems (ADACS) based on their reaction wheels. The MAI-100 ADACS uses an MAI-101, and the MAI-200 ADACS uses an MAI-201. In addition, the ADACS have added electromagnets, magnetometer, sun sensors and a fully programmed ADACS computer. Specifications for MAI's wheels are listed in Table 5. MAI has delivered 22 reaction wheel systems to date. The first to fly was on the Naval Research Laboratory's CubeSat Experiment (QbX) which launched December 8, 2010 [10]. The life of these products is currently unknown; however, MAI has been running a wheel continuously at their facility for 2 years and it has not yet shown signs of bearing wear [11].

Maryland Aerospace Inc. was founded in 2002 as IntelliTech Microsystems, Inc. The company's name was changed to Maryland Aerospace Inc. in 2010 [12]. MAI is located in Crofton, Maryland.

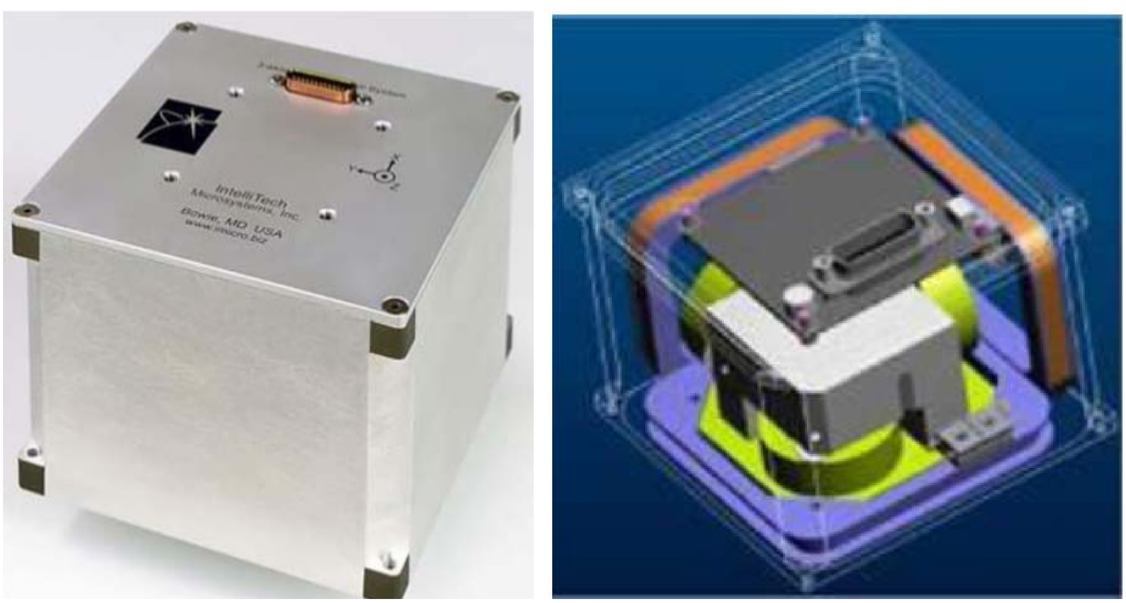


Figure 8. Maryland Aerospace MAI 100 3-Axis ADACS (Image courtesy of Maryland Aerospace)

### 3.4.2 Contact Information

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### 3.4.3 Specifications

Table 5. Maryland Aerospace Inc. Miniature Reaction Wheel Specifications [13][14][15][16]

| Model | MAI-100 | MAI-101 | MAI-200 | MAI-201 |
|---|---|---|---|---|
| **Mass (kg)** | 0.907 (2 lb) | 0.69309 (1.528 lb) | 0.915 (2 lb) | 0.7257 (1.6 lb) |
| **Peak Power (W)** | 4.32 | 2.4 | 9.2 | 4.8 |
| **Average Power (W)** | 2.4 | | | |
| **Bus Voltage (V)** | 12 | 12 | 12 | 12 |
| **Momentum (Nms)** | 0.0011 | 0.002 | 0.0108 | 0.02 |
| **Output Torque (Nm)** | 0.000635 | 0.000635 | 0.000635 | 0.005 |
| **Wheel Speed (RPM)** | 10,000 | 10,000 | 10,000 | 10,000 |
| **Vibration (g-rms)** | 10 | 10 | 10 | 10 |
| **Low Temp (C)** | -40 | -40 | -40 | -40 |
| **High Temp (C)** | 80 | 80 | 80 | 80 |
| **Dimensions (cm)** | 3.937 x 3.937 x 3.1 in | 3 x 3 x 2.75 in | 3.97 x 3.97 x 3.1 in | 3 x 3 x 3 in |
| **Electronics Included** | Yes | Yes | Yes | Yes |
| **Radiation (Krad)** | 30 | 30 | 30 | 30 |
| **Operational Life (years)** | Unknown | Unknown | Unknown | Unknown |
| **Comments** | Complete 3-axis ADACS (Attitude Determination and Control System). Suitable for up to 20 lb Nanosatellites. | 3-axis Miniature Reaction Wheel suitable for up to about 20 lb. nanosatellites. | Complete 3-axis ADACS (Attitude Determination and Control System). Suitable for up to 50 lb microsatellites. | 3-axis Miniature Reaction Wheel suitable for up to about 50 lb microsatellites. |

### 3.5 Bradford Engineering

#### 3.5.1 General Comments

Bradford manufactures 3 reaction wheel models: the W05, W18, and W45. The series has angular momentum capacities ranging from 3 to 70 Nms and torques from 0.1 to 0.3 Nm. All three wheels operate at speeds up to 6,000 RPM. Specifications for Bradford's wheel are listed in Table 6. Bradford wheels have been used on the following missions: Olympus, SOHO, Radarsat, Seastar, Skynet-4, XMM, Integral, Rosetta, and ADM Aeolus [17].

Bradford is located in The Netherlands.

Figure 9. Bradford Engineering Reaction Wheel Assembly (Image courtesy of Bradford Engineering)

#### 3.5.2 Contact Information

Bradford Engineering B.V.
De Wijper 26
4726 TG Heerle (NB)
The Netherlands
Phone: +31 (0)165 – 305 100
Fax: +31 (0)165 – 304 422
E-mail: info@bradford-space.com
Web: http://www.bradford-space.com/

### 3.5.3 Specifications

Table 6. Bradford Engineering Reaction Wheel Specifications [17]

| Model | W05 | W18 | W45 |
|---|---|---|---|
| **Mass (kg)** | 3.2 | 4.95 | 6.95 |
| **Peak Power (W)** | 73 | 63 | 64 |
| **Average Power (W)** | 16 | 17 | 17 |
| **Bus Voltage (V)** | 22-55 | 22-55 | 22-55 |
| **Momentum (Nms)** | 3-7 | 7-28 | 20-70 |
| **Output Torque (Nm)** | 0.1 | 0.2 | 0.3 |
| **Wheel Speed (RPM)** | 6000 | 6000 | 6000 |
| **Dimensions (cm)** | 23.5 dia x 12.3 | 29.5 dia x 12.3 | 36.5 dia x 12.3 |
| **Electronics Included** | No | No | No |
| **Electronics Mass (kg -- if not included)** | 2.2 | 2.2 | 2.2 |
| **Electronics Dimensions (cm)** | 29.1 x 25.9 x 18.1 (8.1 x 25.9 x 18.1/channel) | 29.1 x 25.9 x 18.1 (8.1 x 25.9 x 18.1/channel) | 29.1 x 25.9 x 18.1 (8.1 x 25.9 x 18.1/channel) |
| **Missions/Built for Flight** | Olympus, SOHO, Radarsat, Seastar, Skynet-4, XMM, Integral, Rosetta, ADM Aeolus | Olympus, SOHO, Radarsat, Seastar, Skynet-4, XMM, Integral, Rosetta, ADM Aeolus | Olympus, SOHO, Radarsat, Seastar, Skynet-4, XMM, Integral, Rosetta, ADM Aeolus |
| **Operational Life (years)** | 10 | 10 | 10 |
| **Comments** | 3 different drive electronics options, analogue voltage command, MACS bus, MIL_STD_1553B Bus | 3 different drive electronics options, analogue voltage command, MACS bus, MIL_STD_1553B Bus | 3 different drive electronics options, analogue voltage command, MACS bus, MIL_STD_1553B Bus |

## 3.6 Microsat Systems Canada Inc.

### 3.6.1 General Comments

MSCI manufactures three models of reaction wheels for small satellites: MicroWheel 200, 1000 and 4000. The MicroWheel 200 has 0.18 Nms momentum capacity and 30 mNm torque capability. The MicroWheel 1000 has 1.1 Nms momentum capacity and 30 mNm torque capability. The MicroWheel 4000 has 4.0 Nms momentum capacity and 100 mNm torque capability. The top speed for all three models is 10,000 RPM. Specifications for MSCI's wheels are listed in Table 7. MicroWheel 200s were used on the following missions: FedSat, ChipSat, MOST, NPSat1, Xsat, NEOSat [18]. MicroWheel 1000s were used on the following programs: Tacsat2, Egyptsat, Proba 2, DSE, STP/SIV STPSat-2, Quicksat, MS 28, LADEE, STP/SIC STPSat-3 [19].

MSCI was formerly the Space Division of Dynacon and is located in Ontario, Canada [20].

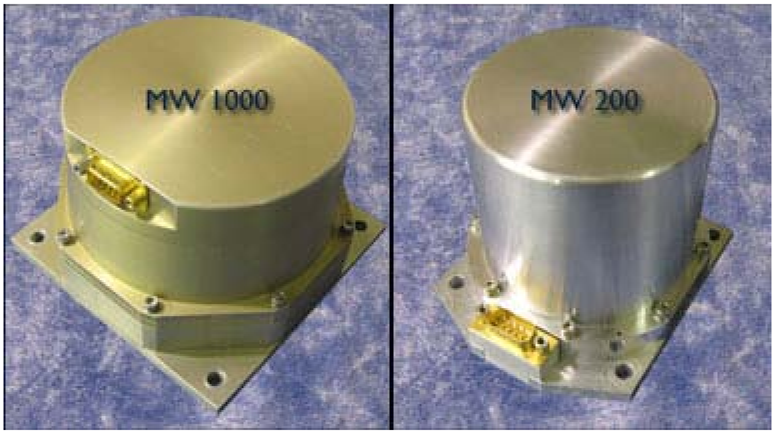


Figure 10. Microsat Systems Canada Inc. MicroWheels (Image courtesy of MSCI)

### 3.6.2 Contact Information

Microsat Systems Canada, Inc.
6870 Goreway Drive,
Mississauga, Ontario, Canada
L4V 1P1
Phone: (905) 364-0388
Fax: (905) 364-0389
E-mail: info@mscinc.ca
Web: www.mscinc.ca

### 3.6.3 Specifications

Table 7. Microsat Systems Canada Inc. MicroWheel Specifications

| Model | MicroWheel 200 [21][18] | MicroWheel 1000 [22][19] | MicroWheel 4000 [23] |
|---|---|---|---|
| **Mass (kg)** | 1 | 1.4 | 2.5 |
| **Peak Power (W)** | 8 | 8 | 16 |
| **Average Power (W)** | 3 | 3 | 3.5 |
| **Bus Voltage (V)** | 28 +/- 6 | 28 +/- 6 | 28 +/- 6 |
| **Momentum (Nms)** | 0.18 | 1.1 | 4 |
| **Output Torque (Nm)** | 0.03 | 0.03 | 0.1 |
| **Wheel Speed (RPM)** | 10000 | 10000 | 10000 |
| **Low Temp (C)** | -30 | -30 | -30 |
| **High Temp (C)** | 60 | 60 | 60 |
| **Dimensions (cm)** | 10 x 10 x 9 | 13 x 13 x 9 | 20 x 20 x 10 |
| **Electronics Included** | Yes | Yes | Yes |
| **Missions/Built for Flight** | FedSat, ChipSat, MOST, NPSat1, Xsat, NEOSat [18] | Tacsat2, Egyptsat, Proba 2, DSE, STP/SIV STPSat-2, Quicksat, MS 28, LADEE, STP/SIC STPSat-3 [19] | Qualification testing completed; first flight units have been delivered but not flown |
| **Radiation (Krad)** | N/A | N/A | 50 |
| **Operational Life (years)** | 5 | 5 | 10 |
| **Comments** | Optional rate sensor available; Asynchronous RS-422/485 | Optional rate sensor available; Asynchronous RS-422/485 | Optional rate sensor available; Asynchronous RS-422/485 |

## 3.7 Rockwell Collins

### 3.7.1 General Comments

Rockwell Collins manufactures the TELDIX line of reaction wheels. The TELDIX line consists of 19 wheels, 17 with a traditional ball bearing design and two with a magnetic bearing design. Rockwell's wheels range from 0.1 to 68 Nms momentum capacity, 5 to 400 mNm, and speeds up to 10,000 RPM. Specifications for Rockwell Collins' wheels are listed in Table 8. Approximately 850 TELDIX Space Wheels have been installed in over 300 satellites [24].

Rockwell Collins Deutschland GmbH is located in Heidelberg, Germany. The company was founded in 1960 as TELDIX GmbH and has changed hands several times since then. It has been owned by Bosch GmbH, Litton Industries Inc., and the Northrop Grumman Corporation before finally being acquired by Rockwell Collins in 2005 [25].

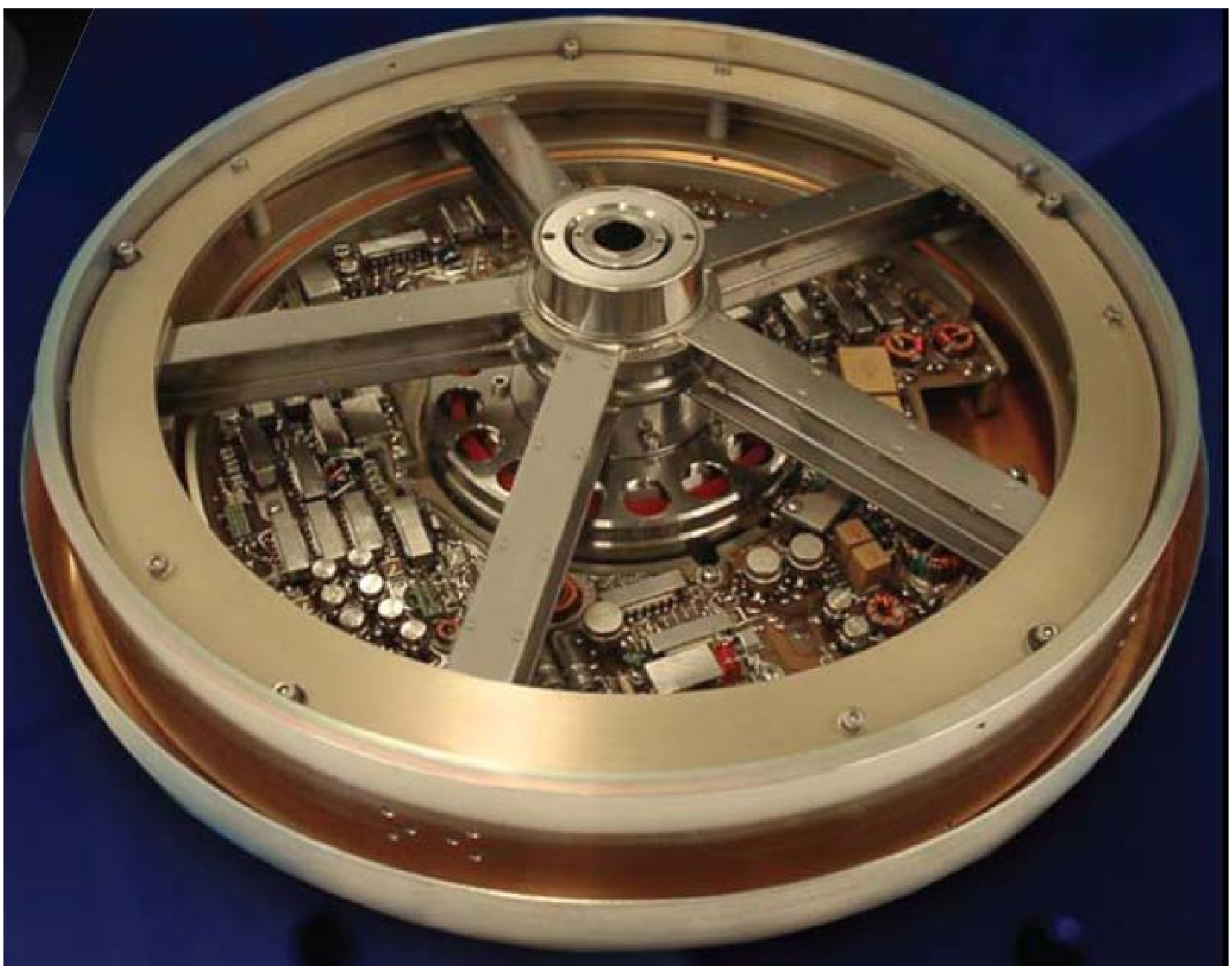

Figure 11. Rockwell Collins TELDIX Reaction Wheel (Image courtesy of Rockwell Collins)

### 3.7.2 Contact Information

Peter Lust Jr (U.S. Representative/Contractor for Rockwell Collins Deutschland)
Electronic Note Space Systems L.L.C.
300 Esplanade Drive, Suite 900
Oxnard, California 93036
Phone: 805-981-9178
Fax: 805-981-9147
E-mail: Peter.Lust@ElectronicNote.com
Web: http://www.rockwellcollins.com/Worldwide/Europe/Germany.aspx

### 3.7.3 Specifications

Table 8a. Rockwell Collins TELDIX Reaction Wheel Specifications

| Model | RSI 01-5/15 [26] | RSI 01-5/28i [26] | RSI 02-33/30A [27] | RSI 04-33/60A [27] | RSI 1.6-33/60A [27] |
|---|---|---|---|---|---|
| Mass (kg) | 0.6 | 0.7 | 1.75 | 1.75 | 2.45 |
| Peak Power (W) | 4 | 4 | 20 | 28 | 28 |
| Average Power (W) | 2 | 2 | 10 | 17 | 17 |
| Bus Voltage (V) | 14 +/- 3; 5 +/- 0.25 | 20 +/- 0.5; 5 +/- 0.25 | 23 to 30 | 23 to 30 | 23 to 30 |
| Momentum (Nms) | 0.04 | 0.12 | 0.2 | 0.4 | 1.6 |
| Output Torque (Nm) | 0.005 | 0.005 | 0.033 | 0.033 | 0.033 |
| Wheel Speed (RPM) | 1500 | 2800 | 15000 | 15000 | 15000 |
| Low Temp (C) | -20 | -20 | -10 | -10 | -10 |
| High Temp (C) | 60 | 60 | 45 | 45 | 45 |
| Dimensions (cm) | 9.5 dia X 10.2 | 9.5 dia X 10.2 | 13.55 dia X 11.0 | 13.55 dia X 11.0 | 13.55 dia X 11.0 |
| Electronics Included | Yes | Yes | Yes | Yes | Yes |
| Missions/Built for Flight | 154 flight models delivered, 75 launched | satellites 30-100 kg | for satellites 100 - 500 kg | for satellites 100 - 500 kg | for satellites 100 - 500 kg |
| Operational Life (years) | 5 | 5 | 15 | 15 | 15 |
| Comments | RS 485 interface | RS 485 interface | RS 485 interface | RS 485 interface | RS 485 interface |

Table 8b. Rockwell Collins TELDIX Reaction Wheel Specifications

| Model | RSI 4-75/60 [28] | RSI 12-75/60 [28] | RSI 15-215/20 [29] | RSI 45-75/60 [29] | RSI 25-75/60 [30] |
|---|---|---|---|---|---|
| **Mass (kg)** | 3.7 | 4.85 | 7.7 | 7.7 | 6.3 |
| **Peak Power (W)** | 90 | 90 | 90 | 90 | 90 |
| **Average Power (W)** | 20 | 20 | 15 | 22 | 20 |
| **Bus Voltage (V)** | 24 to 51 | 24 to 51 | 21 to 37 | 21 to 37 | 24 to 51 |
| **Momentum (Nms)** | 4 | 12 | 15 | 45 | 25 |
| **Output Torque (Nm)** | 0.075 | 0.075 | 0.215 | 0.075 | 0.075 |
| **Wheel Speed (RPM)** | 6000 | 6000 | 2000 | 6000 | 6000 |
| **Low Temp (C)** | -20 | -20 | -20 | -20 | -20 |
| **High Temp (C)** | 70 | 70 | 65 | 65 | 70 |
| **Dimensions (cm)** | 22.2 dia X 8.5 | 24.7 dia X 8.5 | 31 dia X 16 | 31 dia X 16 | 34.7 dia X 11.8 |
| **Electronics Included** | Yes | Yes | Yes | Yes | Yes |
| **Missions/Built for Flight** | for satellites 200-1000 kg | for satellites 200-1000 kg | for satellites 500-1500 kg | for satellites 500-1500 kg | for satellites 1500 - 5000 kg |
| **Operational Life (years)** | 15 | 15 | 15 | 15 | 15 |
| **Comments** | Temp is for synthetic oil; analog interface | Temp is for synthetic oil; analog interface | Analog interface | Analog interface | Analog interface |

Table 8c. Rockwell Collins TELDIX Reaction Wheel Specifications

| **Model** | **RSI 68-75/60 [30]** | **RSI 18-220/45 [31]** | **RSI 30-280/30 [31]** | **RSI 68-170/60 [31]** | **MWI 30-400/37 [32]** |
|---|---|---|---|---|---|
| **Mass (kg)** | 8.5 | 6.3 | 8.5 | 8.9 | 15.3 |
| **Peak Power (W)** | 90 | 150 | 150 | 150 | 300 |
| **Average Power (W)** | 20 | 20 | 20 | 20 | 20 |
| **Bus Voltage (V)** | 24 to 51 | 98 to 102 | 98 to 102 | 98 to 102 | 23 to 37 (optional 50) VDC |
| **Momentum (Nms)** | 68 | 18 | 30 | 68 | 30 |
| **Output Torque (Nm)** | 0.075 | 0.22 | 0.28 | 0.17 | 0.4 |
| **Wheel Speed (RPM)** | 6000 | 4500 | 3000 | 6000 | 3700 |
| **Low Temp (C)** | -20 | -20 | -20 | -20 | -40 |
| **High Temp (C)** | 70 | 70 | 70 | 70 | 70 |
| **Dimensions (cm)** | 34.7 dia X 11.8 | 34.7 dia X 12.4 | 34.7 dia X 12.4 | 34.7 dia X 12.4 | 30.0 dia X 15.0 |
| **Electronics Included** | Yes | Yes | Yes | Yes | Yes |
| **Missions/Built for Flight** | for satellites 1500 - 5000 kg | for satellites 1500 - 5000 kg | for satellites 1500 - 5000 kg | for satellites 1500 - 5000 kg | |
| **Operational Life (years)** | 15 | 15 | 15 | 15 | 20 |
| **Comments** | Analog interface | PWM interface | PWM interface | PWM interface | Gimbaled rotor capacity of +/- 1.7 deg; CAN, RS232, or RS422/RS485 interface |

Table 8d. Rockwell Collins TELDIX Reaction Wheel Specifications

| Model | MWI 100-100/100 [32] | RDR 23-0 [33] | RDR 57-0 [33] | RDR 68-3 [33] |
|---|---|---|---|---|
| Mass (kg) | 16.5 | 5.5 | 7.6 | 7.6 |
| Peak Power (W) | 300 | 90 | 90 | 90 |
| Average Power (W) | 35 | 20 | 20 | 20 |
| Bus Voltage (V) | 24 to 37 (optional 50) VDC | 24 to 51 | 24 to 51 | 24 to 51 |
| Momentum (Nms) | 100 | 23 | 57 | 68 |
| Output Torque (Nm) | 0.1 | 0.09 | 0.09 | 0.075 |
| Wheel Speed (RPM) | 10000 | 5250 | 5250 | 6000 |
| Low Temp (C) | -40 | -20 | -20 | -20 |
| High Temp (C) | 70 | 70 | 70 | 70 |
| Dimensions (cm) | 30.0 dia X 15.0 | 34.5 dia X 11.8 | 34.5 dia X 11.8 | 34.5 dia X 11.8 |
| Electronics Included | Yes | No | No | No |
| Electronics Mass (kg -- if not included) | N/A | 2.1 | 1.45 | 1.25 |
| Electronics Dimensions (cm) | N/A | 17 x 22 x 5.6 | 17 x 22 x 5.6 | 5.2 x 24.7 x 14.5 |
| Missions/Built for Flight | | for satellites 1500 - 5000 kg | for satellites 1500 - 5000 kg | for satellites 1500 - 5000 kg |
| Operational Life (years) | 20 | 15 | 15 | 15 |
| Comments | Gimbaled rotor capacity of +/- 1.7 deg; CAN, RS232, RS422/RS485 interface options | Temp range for synthetic oil; analog interface | Temp range for synthetic oil; analog interface | Temp range for synthetic oil; analog interface |

## 3.8 Surrey Satellite Technology Ltd.

### 3.8.1 General Comments

Surrey's reaction wheel series consists of three wheels suitable for small satellites in their Mircowheel series: 10SP-M, 100SP-M, and 200SP. Surrey's wheels range from 0.42 to 12 Nms momentum capacity, 10 to 200 mNm torque, and the maximum wheel speed of all three is 5,000 RPM. Specifications for Surrey's wheels are listed in Table 9. The proven design life of Surrey's wheels is 7.5 years. The 10SP-M was used on the following missions: Deimos-1, UK-DMC2, NigeriaSat-2, and NX. The 100SP-M was qualified early 2010 and was used on the UK-DMC2 mission. The 200SP was used on the following missions: Giove-A, NigeriaSat-2, and Vniiem.

Surrey was founded in the late 1970s building small satellites. It sells individual components originally developed for its satellites. Surrey is located in England, but has opened Surrey Satellite Technology US LLC as a US based subsidiary that is developing capability for domestic manufacture, integration, test, launch and operation in Englewood, Colorado.[34]

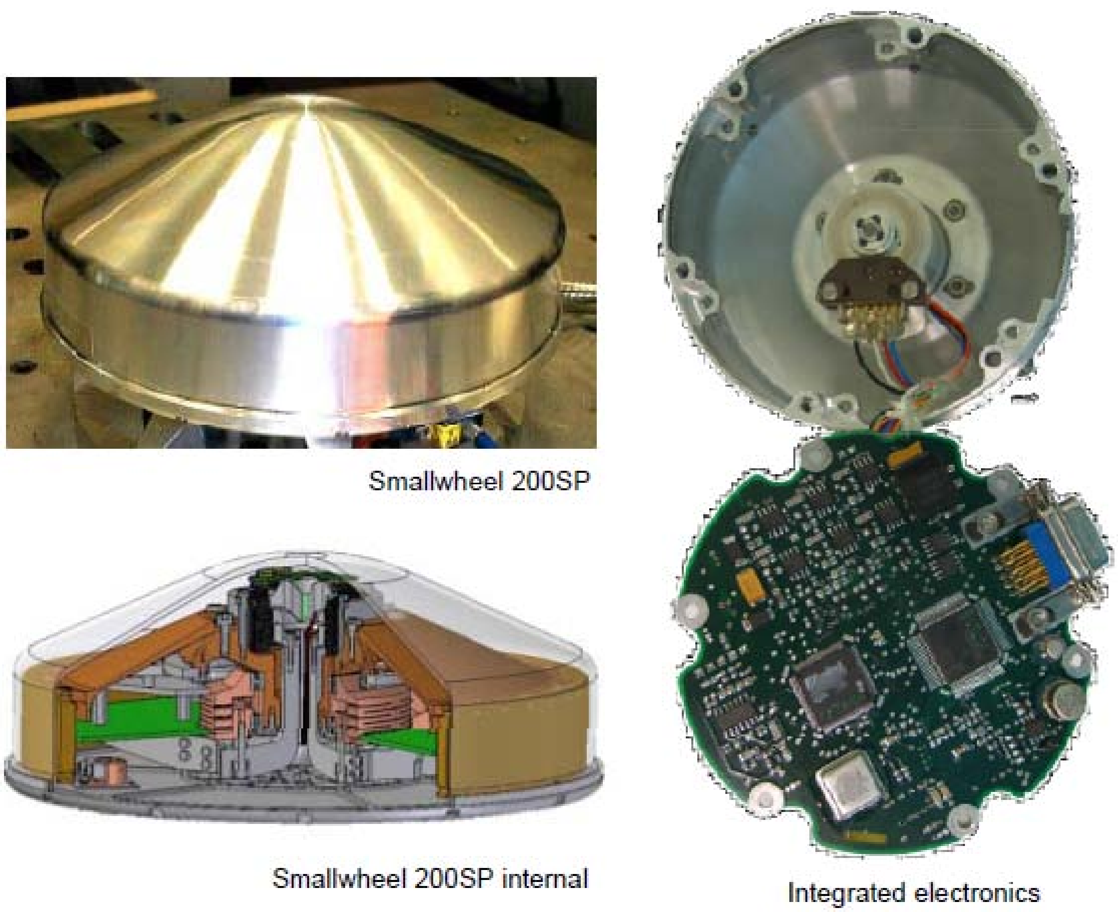


Figure 12. Surry Reaction Wheels (Image courtesy of Surrey)

### 3.8.2 Contact Information

Surrey Satellite Technology US
8310 South Valley Highway, 3rd Floor
Englewood, CO 80112
Telephone: (303) 790-0653
Fax: (303) 792-2386
Email: info@sst-us.com
Web: http://www.sst-us.com/

### 3.8.3 Specifications

Table 9. Surrey Satellite Technology Reaction Wheel Specifications

| **Model** | **Microwheel 10SP-M [35]** | **Microwheel 100SP-M [36]** | **Smallwheel 200SP [37]** |
|---|---|---|---|
| **Mass (kg)** | 0.96 | 2 | 4.9 |
| **Peak Power (W)** | 11.5 | 80 | 120 |
| **Average Power (W)** | 0.7 | 5 | 16 |
| **Bus Voltage (V)** | 28 +/- 4 | 28 +/- 4 | 28 +/- 4 |
| **Momentum (Nms)** | 0.42 | 1.5 | 12 |
| **Output Torque (Nm)** | 0.01 | 0.1 | 0.2 |
| **Wheel Speed (RPM)** | 5000 | 5000 | 5000 |
| **Vibration (g-rms)** | 18 | 18 | 15 |
| **Low Temp (C)** | -20 | -20 | -20 |
| **High Temp (C)** | 50 | 50 | 50 |
| **Dimensions (cm)** | 10 X 10 X 9 | 12 X 12 X 10 | 24 dia X 9 |
| **Electronics Included** | Yes | Yes | Yes |
| **Missions/Built for Flight** | Deimos-1(2008), UK-DMC2(2 units, 2008), NigeriaSat-2(2009), NX (2009) | small LEO s/c, earth observation missions | Giove-A(2005), NigeriaSat-2(2009), Vniiem(2009) |
| **Radiation (Krad)** | | | 100 |
| **Operational Life (years)** | 7.5 | 7.5 | 7.5 |
| **Comments** | CAN or RS422 interface options | Qualified Q1 2010, CAN or RS422 interface options | RS485 or RS422 interface options |

### 3.9 Reaction Wheel Specification Plots

This section contains some plots of reaction wheel specifications by vendor to give an idea of the product range of each vendor compared to the others. Figure 13 shows momentum vs. mass. Figure 14 shows torque vs. mass. Figure 15 shows torque vs. mass.

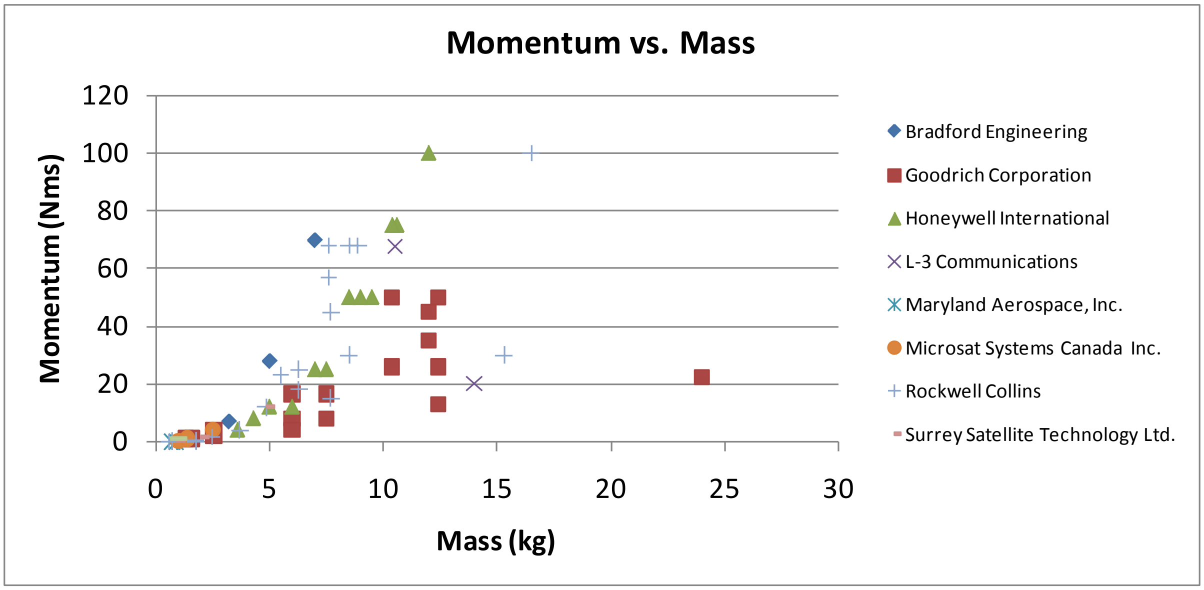


Figure 13. Reaction Wheels Momentum vs. Mass

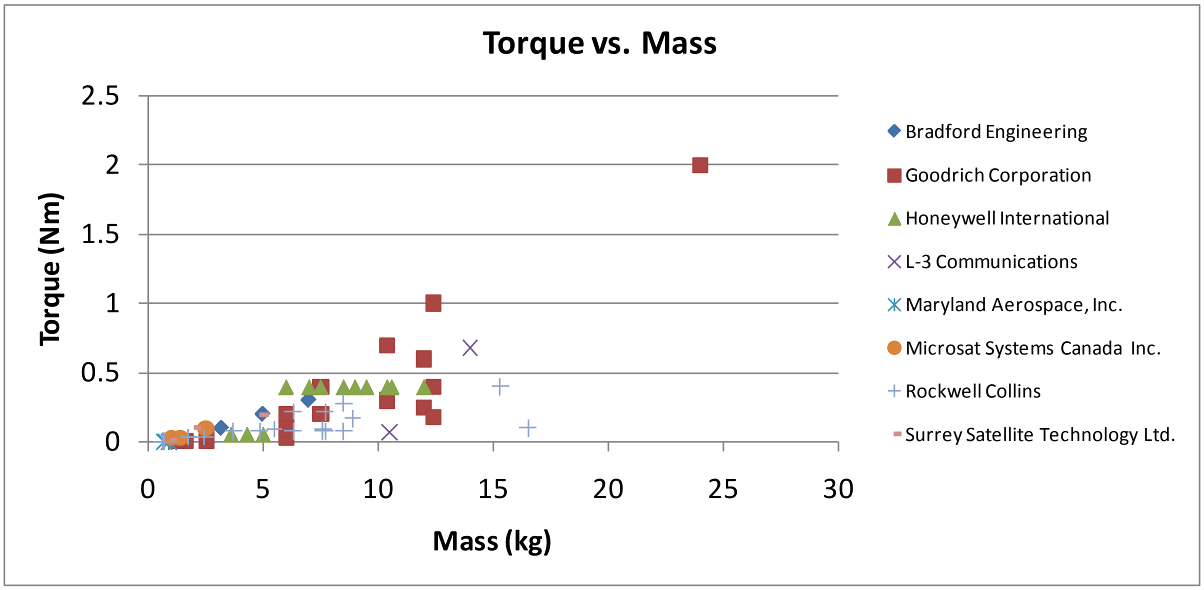


Figure 14. Reaction Wheels Torque vs. Mass

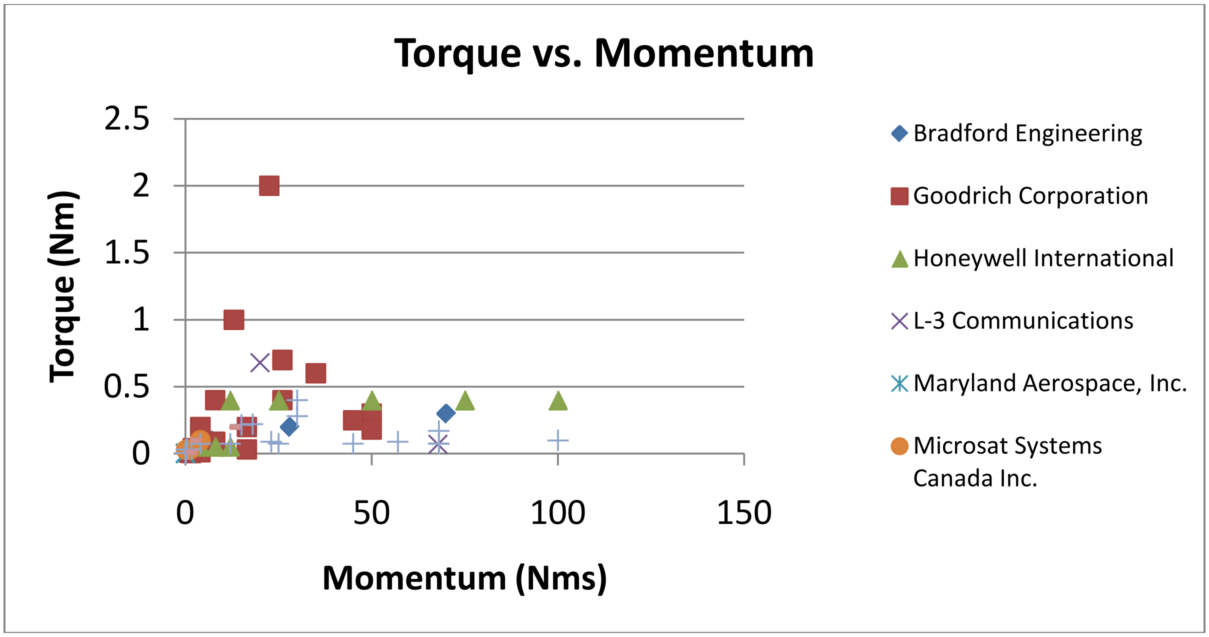


Figure 15. Reaction Wheels Torque vs. Momentum

# 4. Cost and Schedule Performance

## 4.1 Objective and Approach

An effort was made to identify historical cost and schedule performance trends for reaction wheel procurements. The following sources were searched for reaction wheel cost and schedule information: Cost Analysis Data Requirements, project milestone reviews, POP reports, and Aerospace's Space Systems Engineering Database. Data was not readily available from these sources at the reaction wheel level, so results of a previous study [38] were used to identify attitude control system (ACS) level cost growth trends. Trends were used to generate ACS recommendations.

## 4.2 Background and Limitations

ACS cost data was found for the missions listed in Table 10.

Table 10. List of Missions with ACS Cost Data

| Mission | Program | Destination |
|---|---|---|
| **IBEX** | Explorers | Earth Orbiting |
| **Messenger** | Discovery | Planetary |
| **GALEX** | Astrophysics Explorers | Earth Orbiting |
| **Spitzer** | Cosmic Origins | Heliocentric |
| **New Horizons*** | New Frontiers | Planetary |
| **Kepler** | Discovery | Heliocentric |
| **LRO** | Robotic Lunar Exploration | Planetary |

*New Horizons does not use RWAs for attitude control.

ACS cost data was not available at all key milestones (CSR/SRR, PDR, CDR, ATLO Start, Launch). In cases where Launch cost data was not available, pre-launch or CDR data was used instead. In cases where CSR/SRR data was not available, PDR data was used instead.

There is some additional background information about NASA reaction wheel procurement issues that informs some of the results. Reaction wheel on-orbit anomalies on two separate NASA missions occurred while several other NASA missions were procuring similar wheels from the same vendor. This anomaly affected the development of several NASA missions, two of which are included in this study and three of which are not. In one of the cases not included in this study, wheels procured by a mission in development were taken apart and workmanship issues were discovered. The other two missions not included in this study pursued accelerated life tests of the reaction wheels used on those missions which were similar to those that failed on-orbit. The first included additional vendor oversight and changes to the operations plan. The second included additional vibration tests and design analysis.

## 4.3 Results

Figure 16 shows the total percentage cost growth for each mission in blue and the total absolute cost growth in green. The data shows that there is a wide range in cost growth for ACS subsystem with percentage cost growth ranging from 6 to 67 percent and absolute cost growth ranging from $0.1M to $8.4M. The average percentage cost growth is 30 percent, and the average absolute cost growth is $3.7M.

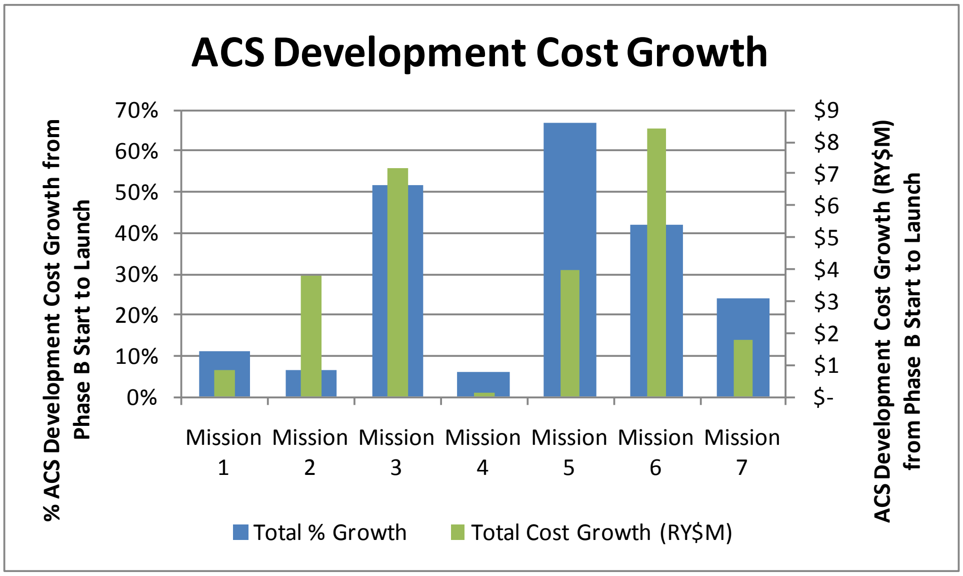


Figure 16. ACS Development Cost Growth

Figure 17 shows the cost at each milestone for the 7 missions. Data was not available for all missions at all milestones, which is why there are some gaps in the data.

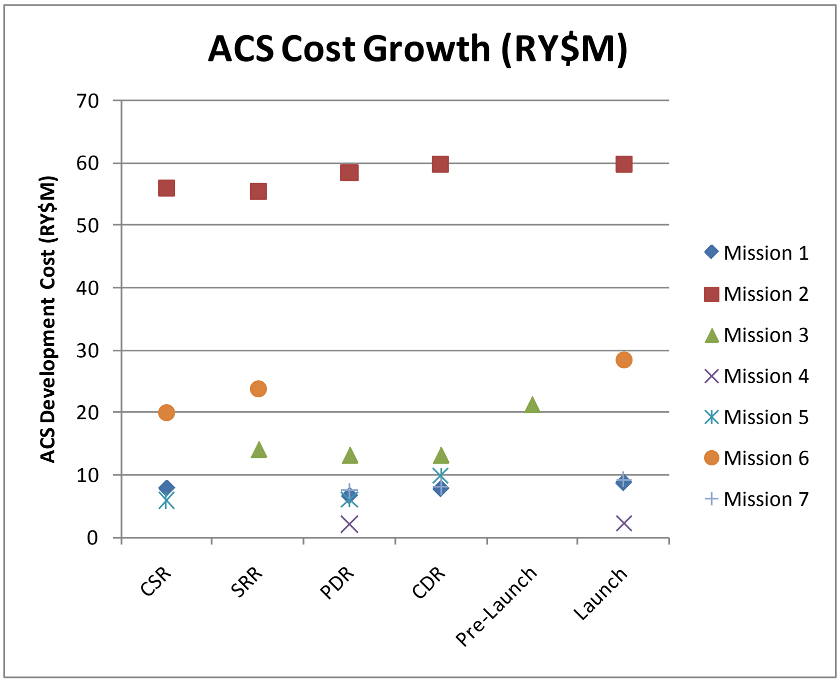


Figure 17. ACS Cost Growth for Each Mission

The on-orbit reaction wheel anomalies mentioned earlier occurred during integration and test for both Mission 3 and Mission 5. A tiger team was formed to evaluate Mission 3's reaction wheels. The tiger team determined that no reaction wheel modifications were required. It was during this same period that Mission 3 experienced significant ADCS cost growth. It is not certain whether all of the ADCS cost growth for Mission 3 was due to the reaction wheel tiger team, but no other issues are known. Mission 5 also formed a reaction wheel tiger team as a result of the on-orbit anomaly. The tiger team found workmanship issues with the reaction wheels that required changes. Flight Program Reviews indicated a cost impact due to these changes, but the impact was not reported, and the cost of the ACS subsystem is not available after CDR. Mission 5 likely experienced further ACS cost growth after CDR that is not shown in the available data.

Figure 18 shows the average cost growth of each spacecraft bus subsystem for the same 7 missions. The data indicates that the ACS is one of the lowest contributors to cost growth, both absolute and percentage.

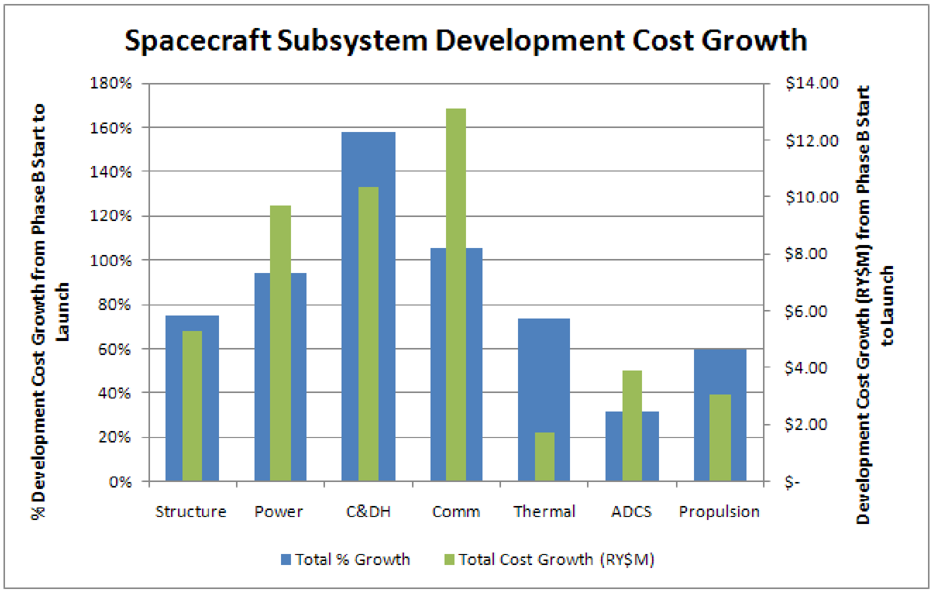


Figure 18. Spacecraft Subsystem Development Cost Growth

### 4.4 Recommendations Based on Cost and Schedule Analysis

Given that cost and schedule performance data is not readily available at the reaction wheel level or ACS subsystem level, a firm conclusion regarding cost and schedule planning cannot be made; however based on the limited information available and taking into account recent reaction wheel procurement issues it may be prudent to hold 30% reserves at the ACS subsystem level.

## 5. Conclusion

The Aerospace Corporation performed a survey of reaction wheel suppliers. Reaction wheel vendor and product information was gathered from non-sensitive internal resources, the internet, and communications with vendors. The information presented included: general information on each reaction wheel vendor and a listing of the available reaction wheel models along with performance capabilities, specifications, and flight history. Additionally, historical cost and schedule performance was analyzed for the Attitude Determination and Control Subsystem (ADCS) and correlated to reaction wheel procurements. The historical cost and schedule performance results led to a recommendation to hold 30% cost reserves at the ACS subsystem level.

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# Appendix A. Reaction Wheel Database

| Manufacturer | Model | Mass (kg) | Peak Power (W) | Average Power (W) | Bus Voltage (V) | Momentum (N-m-sec) | Output Torque (N-m) | Wheel Speed (RPM) | Vibe (g-rms) | Low Temp (C) | Hi Temp (C) | Dimensions (cm) | Electronics Included | Electonics Mass (kg -- if not included) | Electronics Dimensions (cm) | Missions/Built for Flight | Rad-iation (Krad) | Operational Life (years) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bradford Engineering** | **W05** | 3.2 | 73 | 16 | 22-55 | 3-7 | 0.1 | 6,000 | | | | 23.5 dia x 12.3 | No | 2.2 | 29.1 x 25.9 x 18.1 (8.1 x 25.9 x 18.1/channel) | Olympus, SOHO, Radarsat, Seastar, Skynet-4, XMM, Integral, Rosetta, ADM Aeolus | | 10 | 3 different drive electronics options, analogue voltage command, MACS bus, MIL_STD_1553B Bus |
| **Bradford Engineering** | **W18** | 5.0 | 63 | 17 | 22-55 | 7-28 | 0.2 | 6,000 | | | | 29.5 dia x 12.3 | No | 2.2 | 29.1 x 25.9 x 18.1 (8.1 x 25.9 x 18.1/channel) | Olympus, SOHO, Radarsat, Seastar, Skynet-4, XMM, Integral, Rosetta, ADM Aeolus | | 10 | 3 different drive electronics options, analogue voltage command, MACS bus, MIL_STD_1553B Bus |
| **Bradford Engineering** | **W45** | 7.0 | 64 | 17 | 22-55 | 20-70 | 0.3 | 6,000 | | | | 36.5 dia x 12.3 | No | 2.2 | 29.1 x 25.9 x 18.1 (8.1 x 25.9 x 18.1/channel) | Olympus, SOHO, Radarsat, Seastar, Skynet-4, XMM, Integral, Rosetta, ADM Aeolus | | 10 | 3 different drive electronics options, analogue voltage command, MACS bus, MIL_STD_1553B Bus |
| **Goodrich Corporation** | **TW-1AA8** | 1.6 | 14 | 4 | 28 to 70 | 1 | 0.008 | 6,500 | N/A | N/A | N/A | 13.8 dia x 8.3 | Yes | N/A | N/A | New Product | | | Electronics Included |
| **Goodrich Corporation** | **TW-1.5AA6** | 1.6 | 18 | 4 | 28 to 70 | 1.5 | 0.006 | 10,000 | N/A | N/A | N/A | 13.8 dia x 8.3 | Yes | N/A | N/A | New Product | | | Electronics Included |
| **Goodrich Corporation** | **TW-1AA8** | 1.3 | 13 | 4 | 28 to 70 | 1 | 0.008 | 6,500 | N/A | N/A | N/A | 13.8 dia x 7 | No | 1, 1.5, 2.1, 3 (for 1, 2, 3 or 4 wheels) | 16 x19 x3.8n (n = number of RW) | New Product | | | Electronics Separate |
| **Goodrich Corporation** | **TW-1.5AA6** | 1.3 | 18 | 4 | 28 to 70 | 1.5 | 0.006 | 10,000 | N/A | N/A | N/A | 13.8 dia x 7 | No | 1, 1.5, 2.1, 3 (for 1, 2, 3 or 4 wheels) | 16 x19 x3.8n (n = number of RW) | New Product | | | Electronics Separate |
| **Goodrich Corporation** | **TW-4A12** | 2.55 | 25 | 5 | 28 to 70 | 4 | 0.012 | 5,100 | N/A | N/A | N/A | 20.5 dia x 6.4 | No | 1, 1.5, 2.1, 3 (for 1, 2, 3 or 4 wheels) | 16 x19 x3.8n (n = number of RW) | LEO, GEO, and Interplanetary missions | | | Electronics Separate |
| **Goodrich Corporation** | **TW-2A40** | 2.55 | 25 | 5 | 28 to 70 | 2 | 0.04 | 2,550 | N/A | N/A | N/A | 20.5 dia x 6.4 | No | 1, 1.5, 2.1, 3 (for 1, 2, 3 or 4 wheels) | 16 x19 x3.8n (n = number of RW) | LEO, GEO, and Interplanetary missions | | | Electronics Separate |
| **Goodrich Corporation** | **TW-16B32** | 6 | 50 | 7 | 28 to 70 | 16.5 | 0.032 | 5,100 | N/A | N/A | N/A | 25.5 dia x 12.4 | Yes | N/A | N/A | LEO, Heliocentric, and Interplanetary missions | | | |
| **Goodrich Corporation** | **TW-8B90** | 6 | 55 | 7 | 28 to 70 | 8 | 0.09 | 2,500 | N/A | N/A | N/A | 25.5 dia x 12.4 | Yes | N/A | N/A | LEO, Heliocentric, and Interplanetary missions | | | |
| **Goodrich Corporation** | **TW-4B200** | 6 | 70 | 7 | 28 to 70 | 4 | 0.2 | 1,235 | N/A | N/A | N/A | 25.5 dia x 12.4 | Yes | N/A | N/A | LEO, Heliocentric, and Interplanetary missions | | | |
| **Goodrich Corporation** | **TW-16B200** | 7.5 | 250 | 15 | 28 to 70 | 16.5 | 0.2 | 5,100 | N/A | N/A | N/A | 28.0 dia x 13.5 | Yes | N/A | N/A | LEO, MEO, and GEO missions | | | |
| **Goodrich Corporation** | **TW-8B400** | 7.5 | 250 | 15 | 28 to 70 | 8 | 0.4 | 2,510 | N/A | N/A | N/A | 28.0 dia x 13.5 | Yes | N/A | N/A | LEO, MEO, and GEO missions | | | |
| **Goodrich Corporation** | **TW-45C250** | 12.0 | 250 | 10 | 28 to 70 | 45 | 0.25 | 4,500 | N/A | N/A | N/A | 30.5 dia x 11.5 | Yes | N/A | N/A | New Product | | | |
| **Goodrich Corporation** | **TW-35C600** | 12.0 | 400 | 10 | 28 to 70 | 35 | 0.6 | 3,500 | N/A | N/A | N/A | 30.5 dia x 11.5 | Yes | N/A | N/A | New Product | | | |
| **Goodrich Corporation** | **TW-50E300** | 10.4 | 300 | 22 | 28 to 70 | 50 | 0.3 | 3,900 | N/A | N/A | N/A | 39.4 dia x 16.6 | No | 4.1 | 18 x 18 x 9 | LEO, L-2, and GEO missions | | | |
| **Goodrich Corporation** | **TW-26E700** | 10.4 | 380 | 22 | 28 to 70 | 26 | 0.7 | 2,020 | N/A | N/A | N/A | 39.4 dia x 16.6 | No | 4.1 | 18 x 18 x 9 | LEO, L-2, and GEO missions | | | |
| **Goodrich Corporation** | **TW-50E180** | 12.4 | 250 | 22 | 28 to 70 | 50 | 0.18 | 3,900 | N/A | N/A | N/A | 39.4 dia x 18 | Yes | N/A | N/A | LEO missions | | | |

| Manufacturer | Model | Mass (kg) | Peak Power (W) | Average Power (W) | Bus Voltage (V) | Momentum (N-m-sec) | Output Torque (N-m) | Wheel Speed (RPM) | Vibe (g-rms) | Low Temp (C) | Hi Temp (C) | Dimensions (cm) | Electronics Included | Electonics Mass (kg -- if not included) | Electronics Dimensions (cm) | Missions/Built for Flight | Rad-iation (Krad) | Operational Life (years) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Goodrich Corporation** | **TW-26E400** | 12.4 | 250 | 22 | 28 to 70 | 26 | 0.4 | 2,020 | N/A | N/A | N/A | 39.4 dia x 18 | Yes | N/A | N/A | LEO missions | | | |
| **Goodrich Corporation** | **TW-13E1000** | 12.4 | 300 | 22 | 28 to 70 | 13 | 1 | 1,000 | N/A | N/A | N/A | 39.4 dia x 18 | Yes | N/A | N/A | LEO missions | | | |
| **Goodrich Corporation** | **TW-22E2000** | 24.0 | 300 | N/A | 28 to 70 | 22.5 | 2 | 550 | N/A | N/A | N/A | 39.4 dia x 18 | Yes | N/A | N/A | LEO missions | | | |
| **Honeywell International** | **HR--12-12** | 6.0 | 195 | | 14 to 80 | 12 | 0.4 | 6,000 | 13.8 | -30 | 70 | 31.6 dia X 15.9 (31.6 dia x 14.8 w/o electronics) | Optional | | 6 x 16.9 x 23 | Many | 300 | 15 | Option for integrated electronics or separate unit, also 18 and 37.5 N-m-sec designs available |
| **Honeywell International** | **HR-12-25** | 7.0 | 195 | | 15 to 80 | 25 | 0.4 | 6,000 | 13.8 | -30 | 70 | 31.6 dia X 15.9 (31.6 dia x 14.8 w/o electronics) | Optional | | 6 x 16.9 x 23 | Many | 300 | 15 | Option for integrated electronics or separate unit, also 18 and 37.5 N-m-sec designs available |
| **Honeywell International** | **HR-12-50** | 9.5 | 195 | | 16 to 80 | 50 | 0.4 | 6,000 | 13.8 | -30 | 70 | 31.6 dia X 15.9 (31.6 dia x 14.8 w/o electronics) | Optional | | 6 x 16.9 x 23 | Many | 300 | 15 | Option for integrated electronics or separate unit, also 18 and 37.5 N-m-sec designs available |
| **Honeywell International** | **HR-14-25** | 7.5 | 195 | | 17 to 80 | 25 | 0.4 | 6,000 | 13.8 | -30 | 70 | 36.6 dia X 15.9 (36.6 dia x 14.8 w/o electronics) | Optional | | 6 x 16.9 x 23 | Many | 300 | 15 | Option for integrated electronics or separate unit |
| **Honeywell International** | **HR-14-50** | 8.5 | 195 | | 18 to 80 | 50 | 0.4 | 6,000 | 13.8 | -30 | 70 | 36.6 dia X 15.9 (36.6 dia x 14.8 w/o electronics) | Optional | | 6 x 16.9 x 23 | Many | 300 | 15 | Option for integrated electronics or separate unit |
| **Honeywell International** | **HR-14-75** | 10.6 | 195 | | 19 to 80 | 75 | 0.4 | 6,000 | 13.8 | -30 | 70 | 36.6 dia X 15.9 (36.6 dia x 14.8 w/o electronics) | Optional | | 6 x 16.9 x 23 | Many | 300 | 15 | Option for integrated electronics or separate unit |
| **Honeywell International** | **HR-16-50** | 9.0 | 195 | | 20 to 80 | 50 | 0.4 | 6,000 | 13.8 | -30 | 70 | 41.8 dia X 17.8 (41.8 dia x 15.2 w/o electronics) | Optional | | 6 x 16.9 x 23 | Many | 300 | 15 | Option for integrated electronics or separate unit, also 68, 125, and 150 N-m-sec designs |
| **Honeywell International** | **HR-16-75** | 10.4 | 195 | | 21 to 80 | 75 | 0.4 | 6,000 | 13.8 | -30 | 70 | 41.8 dia X 17.8 (41.8 dia x 15.2 w/o electronics) | Optional | | 6 x 16.9 x 23 | Many | 300 | 15 | Option for integrated electronics or separate unit, also 68, 125, and 150 N-m-sec designs |
| **Honeywell International** | **HR-16-100** | 12.0 | 195 | | 22 to 80 | 100 | 0.4 | 6,000 | 13.8 | -30 | 70 | 41.8 dia X 17.8 (41.8 dia x 15.2 w/o electronics) | Optional | | 6 x 16.9 x 23 | Many | 300 | 15 | Option for integrated electronics or separate unit, also 68, 125, and 150 N-m-sec designs |
| **Honeywell International** | **HR0610** | 3.6 to 5.0 | 80 | | 14 to 23 | 4 to 12 | 0.055 | 6,000 | 19.8 | -15 | 60 | 26.7 diam X 12 H | | N/A | N/A | Globstar/active on-orbit | | S equiv, 10 yr life | Modular momentum sizing, 296 RWAs produced which currently supports 56 satellites active on orbit |
| **L-3 Communications** | **MWA-50** | 10.5 | 100 | | 28 +/- 6 | 67.8 | 0.07 | 6,600 | | | | 38.6 dia X 14.2 | Yes | N/A | N/A | IRIDIUM and Indostar | | | |
| **L-3 Communications** | **RWA-15** | 14 | 230 | | 28 +/- 6 | 20 | 0.68 | 2,200 | | | | 36.9 dia x 15.3 | Yes | N/A | N/A | IKONOS, QSCAT, QBIRD, Swift, LEO | 30 | 7 | Analog interface |
| **Maryland Aerospace, Inc.** | **MAI-100** | .907 (2 lb | 4.32 | 2.4 | 12 | 0.0011 | 0.00064 | 10,000 | 10 | -40 | 80 | 3.937 x 3.937 x 3.1 in | Yes | N/A | N/A | Approximately 20 Maryland Aerospace wheels delivered to date. One flown on NRL QbX. | 30 | Unknown | Complete 3-axis ADACS (Attitude Determination and Control System) suitable for up to 20 lb Nanosatellite applications. |
| **Maryland Aerospace, Inc.** | **MAI-101** | 309 (1.52 | 2.4 | | 12 | 0.002 | 0.00064 | 10,000 | 10 | -40 | 80 | 3 x 3 x 2.75 in | Yes | N/A | N/A | Approximately 20 Maryland Aerospace wheels delivered to date. One flown on NRL QbX. | 30 | Unknown | 3-axis Miniature Reaction Wheel suitable for up to about 20 lb. satellite |
| **Maryland Aerospace, Inc.** | **MAI-200** | .915 (2 lb | 9.2 | | 12 | 0.0108 | 0.00064 | 10,000 | 10 | -40 | 80 | 3.97 x 3.97 x 3.1 in | Yes | N/A | N/A | Approximately 20 Maryland Aerospace wheels delivered to date. One flown on NRL QbX. | 30 | Unknown | Complete 3-axis ADACS (Attitude Determination and Control System) suitable for up to 50 lb Nanosatellite applications. |
| **Maryland Aerospace, Inc.** | **MAI-201** | 0.7257 (1.6 lb) | 4.8 | | 12 | 0.02 | 0.005 | 10,000 | 10 | -40 | 80 | 3 x 3 x 3 in | Yes | N/A | N/A | Approximately 20 Maryland Aerospace wheels delivered to date. One flown on NRL QbX. | 30 | Unknown | 3-axis Miniature Reaction Wheel suitable for up to about 50 lb satellite |

| Manufacturer | Model | Mass (kg) | Peak Power (W) | Average Power (W) | Bus Voltage (V) | Momentum (N-m-sec) | Output Torque (N-m) | Wheel Speed (RPM) | Vibe (g-rms) | Low Temp (C) | Hi Temp (C) | Dimensions (cm) | Electronics Included | Electonics Mass (kg -- if not included) | Electronics Dimensions (cm) | Missions/Built for Flight | Rad-iation (Krad) | Operational Life (years) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Microsat Systems Canada Inc.** | **MicroWheel 200** | 1.0 | 8 | 3 | 28 +/- 6 | 0.18 | 0.03 | 10,000 | | -30 | 60 | 10 x 10 x 9 | Yes | N/A | N/A | CSIRO FedSat, SpaceDev ChipSat, Canadian Space Agency MOST, US Navy NPSat1, Nanyang Technological University Singapore Xsat, Canadian Space Agency (MSCI) NEOSat | NA | 5 | Optional rate sensor available; Asynchronous RS-422/485 |
| **Microsat Systems Canada Inc.** | **MicroWheel 1000** | 1.4 | 8 | 3 | 28 +/- 6 | 1.1 | 0.03 | 10,000 | | -30 | 60 | 13 x 13 x 9 | Yes | N/A | N/A | MSI/USAF Tacsat2, Yushnoy/Egypt Egyptsat, Verheart/ESA Proba 2, MDA/SpaceDev DSE, AeroAstro/Ball STP/SIV STPSat-2, Canadian Space Agency Quicksat, Hartron MS 28, NASA Ames LADEE, Ball STP/SIC | NA | 5 | Optional rate sensor available; Asynchronous RS-422/485 |
| **Microsat Systems Canada Inc.** | **MicroWheel 4000** | 2.5 | 16 | 3.5 | 28 +/- 6 | 4 | 0.1 | 10,000 | | -30 | 60 | 20 x 20 x 10 | Yes | N/A | N/A | Qualification testing completed; first flight units have been delivered but not flown | 50 | 10 | Optional rate sensor available; Asynchronous RS-422/485 |
| **Rockwell Collins** | **RSI 01-5/15** | 0.6 | 4 | 2 | 14 +/- 3; 5 +/- 0.25 | 0.04 | 0.005 | 1,500 | | -20 | 60 | 9.5 dia X 10.2 | Yes | N/A | N/A | 154 flight models delivered, 75 launched | | 5 | RS 485 interface |
| **Rockwell Collins** | **RSI 01-5/28i** | 0.7 | 4 | 2 | 20 +/- 0.5; 5 +/- [illegible] | 0.12 | 0.005 | 2,800 | | -20 | 60 | 9.5 dia X 10.2 | Yes | N/A | N/A | satellites 30-100kg | | 5 | RS 485 interface |
| **Rockwell Collins** | **RSI 02-33/30A** | 1.75 | 20 | 10 | 23 to 30 | 0.2 | 0.033 | 15,000 | | -10 | 45 | 13.55 dia X 11.0 | Yes | N/A | N/A | for satellites 100 - 500 kg | | 15 | RS 485 interface |
| **Rockwell Collins** | **RSI 04-33/60A** | 1.75 | 28 | 17 | 23 to 30 | 0.4 | 0.033 | 15,000 | | -10 | 45 | 13.55 dia X 11.0 | Yes | N/A | N/A | for satellites 100 - 500 kg | | 15 | RS 485 interface |
| **Rockwell Collins** | **RSI 1.6-33/60A** | 2.45 | 28 | 17 | 23 to 30 | 1.6 | 0.033 | 15,000 | | -10 | 45 | 13.55 dia X 11.0 | Yes | N/A | N/A | for satellites 100 - 500 kg | | 15 | RS 485 interface |
| **Rockwell Collins** | **RSI 4-75/60** | 3.7 | 90 | 20 | 24 to 51 | 4 | 0.075 | 6,000 | | -20 | 70 | 22.2 dia X 8.5 | Yes | N/A | N/A | for satellites 200-1000 kg | | 15 | temp is for synthetic oil; analog interface |
| **Rockwell Collins** | **RSI 12-75/60** | 4.85 | 90 | 20 | 24 to 51 | 12 | 0.075 | 6,000 | | -20 | 70 | 24.7 dia X 8.5 | Yes | N/A | N/A | for satellites 200-1000 kg | | 15 | temp is for synthetic oil; analog interface |
| **Rockwell Collins** | **RSI 15-215/20** | 7.7 | 90 | 15 | 21 to 37 | 15 | 0.215 | 2,000 | | -20 | 65 | 31 dia X 16 | Yes | N/A | N/A | for satellites 500-1500kg | | 15 | Analog interface |
| **Rockwell Collins** | **RSI 45-75/60** | 7.7 | 90 | 22 | 21 to 37 | 45 | 0.075 | 6,000 | | -20 | 65 | 31 dia X 16 | Yes | N/A | N/A | for satellites 500-1500kg | | 15 | Analog interface |
| **Rockwell Collins** | **RSI 25-75/60** | 6.3 | 90 | 20 | 24 to 51 | 25 | 0.075 | 6,000 | | -20 | 70 | 34.7 dia X 11.8 | Yes | N/A | N/A | for satellites 1500 - 5000 kg | | 15 | Analog interface |
| **Rockwell Collins** | **RSI 68-75/60** | 8.5 | 90 | 20 | 24 to 51 | 68 | 0.075 | 6,000 | | -20 | 70 | 34.7 dia X 11.8 | Yes | N/A | N/A | for satellites 1500 - 5000 kg | | 15 | Analog interface |
| **Rockwell Collins** | **RSI 18-220/45** | 6.3 | 150 | 20 | 98 to 102 | 18 | 0.22 | 4,500 | | -20 | 70 | 34.7 dia X 12.4 | Yes | N/A | N/A | for satellites 1500 - 5000 kg | | 15 | PWM interface |
| **Rockwell Collins** | **RSI 30-280/30** | 8.5 | 150 | 20 | 98 to 102 | 30 | 0.28 | 3,000 | | -20 | 70 | 34.7 dia X 12.4 | Yes | N/A | N/A | for satellites 1500 - 5000 kg | | 15 | PWM interface |
| **Rockwell Collins** | **RSI 68-170/60** | 8.9 | 150 | 20 | 98 to 102 | 68 | 0.17 | 6,000 | | -20 | 70 | 34.7 dia X 12.4 | Yes | N/A | N/A | for satellites 1500 - 5000 kg | | 15 | PWM interface |
| **Rockwell Collins** | **MWI 30-400/37** | 15.3 | 300 | 20 | 23 to 37 (optional 50) VDC | 30 | 0.4 | 3,700 | | -40 | 70 | 30.0 dia X 15.0 | Yes | N/A | N/A | | | 20 | rotor gimballing capacity of +/- 1.7 deg; CAN, RS232, RS422/RS485 interface options |
| **Rockwell Collins** | **MWI 100-100/100** | 16.5 | 300 | 35 | 24 to 37 (optional 50) VDC | 100 | 0.1 | 10,000 | | -40 | 70 | 30.0 dia X 15.0 | Yes | N/A | N/A | | | 20 | rotor gimballing capacity of +/- 1.7 deg; CAN, RS232, RS422/RS485 interface options |
| **Rockwell Collins** | **RDR 23-0** | 5.5 | 90 | 20 | 24 to 51 | 23 | 0.09 | 5,250 | | -20 | 70 | 34.5 dia X 11.8 | No | 2.1 | 17 x 22 x 5.6 | for satellites 1500 - 5000 kg | | 15 | temp range for synthetic oil; analog interface |
| **Rockwell Collins** | **RDR 57-0** | 7.6 | 90 | 20 | 24 to 51 | 57 | 0.09 | 5,250 | | -20 | 70 | 34.5 dia X 11.8 | No | 1.45 | 17 x 22 x 5.6 | for satellites 1500 - 5000 kg | | 15 | temp range for synthetic oil; analog interface |

| Manufacturer | Model | Mass (kg) | Peak Power (W) | Average Power (W) | Bus Voltage (V) | Momentum (N-m-sec) | Output Torque (N-m) | Wheel Speed (RPM) | Vibe (g-rms) | Low Temp (C) | Hi Temp (C) | Dimensions (cm) | Electronics Included | Electonics Mass (kg -- if not included) | Electronics Dimensions (cm) | Missions/Built for Flight | Rad-iation (Krad) | Operational Life (years) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rockwell Collins** | **RDR 68-3** | 7.6 | 90 | 20 | 24 to 51 | 68 | 0.075 | 6,000 | | -20 | 70 | 34.5 dia X 11.8 | No | 1.25 | 5.2 x 24.7 x 14.5 | for satellites 1500 - 5000 kg | | 15 | temp range for synthetic oil; analog interface |
| **Surrey Satellite Technology Ltd.** | **Microwheel 10SP-M** | 0.96 | 11.5 | 0.7 | 28 +/- 4 | 0.42 | 0.01 | 5,000 | 18 | -20 | 50 | 10 X 10 X 9 | Yes | N/A | N/A | Deimos-1(2008), UK-DMC2(2 units, 2008), NigeriaSat-2(2009), NX (2009) | | 7.5 | CAN or RS422 interface options |
| **Surrey Satellite Technology Ltd.** | **Microwheel 100SP-M** | 2 | 80 | 5 | 28 +/- 4 | 1.5 | 0.1 | 5,000 | 18 | -20 | 50 | 12 X 12 X 10 | Yes | N/A | N/A | small LEO s/c, earth observation missions | | 7.5 | Qualified Q1 2010, CAN or RS422 interface options |
| **Surrey Satellite Technology Ltd.** | **Smallwheel 200SP** | 4.9 | 120 | 16 | 28 +/- 4 | 12 | 0.2 | 5,000 | 15 | -20 | 50 | 24 dia X 9 | Yes | N/A | N/A | Giove-A(2005), NigeriaSat-2(2009), Vniiem(2009) | 100 | 7.5 | RS485 or RS422 interface options |