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Chapter Glossary

(ADCS)	Attitude Determination and Control System
(CoCom)	Coordinating Committee for Multilateral Export Controls
(COTS)	Commercial-off-the-Shelf
(DOF)	Degrees of Freedom
(DSAC)	Deep Space Atomic Clock
(DSN)	Deep Space Network
(EAR)	Export Administration Regulations
(FOGs)	Fiber Optic Gyros
(GNC)	Guidance, Navigation & Control
(GSO)	Geo-stationary Orbit
(USAF)	U.S. Air Force
(HCI)	Horizon Crossing Indicators
(IMUs)	Inertial Measurement Units
(JPL)	Jet Propulsion Laboratory
(Lidar)	Light Detection and Ranging
(LMRST)	Low Mass Radio Science Transponder
(MarCO)	Mars Cube One
(PMSM)	Permanent-magnet Synchronous Motor
(SDST)	Small Deep Space Transponder
(SWaP)	Size, weight, and power
(TLE)	Two-Line Element
(TRL)	Technology Readiness Level

5.0 Guidance, Navigation & Control

5.1 Introduction

The Guidance, Navigation & Control (GNC) subsystem includes the components used for position determination and the components used by the Attitude Determination and Control System (ADCS). In Earth orbit, onboard position determination can be provided by a Global Positioning System (GPS) receiver. Alternatively, ground-based radar tracking systems can also be used. If onboard knowledge is required, then these radar observations can be uploaded and paired with a suitable propagator. Commonly, the U.S. Air Force (USAF) publishes Two-Line Element sets (TLE) (1), which are paired with a SGP4 propagator (2). In deep space, position determination is performed using the Deep Space Network (DSN) and an onboard radio transponder (3). There are also technologies being developed that use optical detection of celestial bodies such as planets and X-ray pulsars to calculate position data (23).

Using SmallSats in cislunar space and beyond requires a slightly different approach than the GNC subsystem approach in low-Earth orbit. Use of the Earth's magnetic field, for example, is not possible in these missions, and alternate ADCS designs and methods must be carefully considered. Two communication relay CubeSats (Mars Cube One, MarCO) successfully demonstrated such interplanetary capability during the 2018 Insight mission to Mars (4). This interplanetary mission demonstrated both the capability of this class of spacecraft and the GNC fine pointing design for communication in deep space.

ADCS includes sensors to determine attitude and spin rate, such as star trackers, sun sensors, horizon sensors, magnetometers, and gyros. In addition, the ADCS is often used to control the vehicle during trajectory correction maneuvers and, using accelerometers, to terminate maneuvers when the desired velocity change has been achieved. Actuators are designed to change a spacecraft's attitude and to impart velocity change during trajectory correction maneuvers. Common spacecraft actuators include magnetic torquers, reaction wheels, and thrusters. There are many attitude determination and control architectures and algorithms suitable for use in small spacecraft (5).

Miniaturization of existing technologies is a continuing trend in small spacecraft GNC. While three-axis stabilized, GPS-equipped, 100 kg class spacecraft have been flown for decades, it has only been in the past few years that such technologies have become available for micro- and nano-class spacecraft. Table 5-1 summarizes the current state-of-the-art of performance for GNC subsystems in small spacecraft. Performance greatly depends on the size of the spacecraft and values will range for nano- to micro-class spacecraft.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

Table 5-1: State-of-the-Art GNC Subsystems		
Component	**Performance**	**TRL**
Reaction Wheels	0.00023 – 0.3 Nm peak torque, 0.0005 – 8 N m s storage	7-9
Magnetic Torquers	0.15 A m^2 – 15 A m^2	7-9
Star Trackers	8 arcsec pointing knowledge	7-9
Sun Sensors	0.1° accuracy	7-9
Earth Sensors	0.25° accuracy	7-9
Inertial Sensors	Gyros: 0.15° h^{-1} bias stability, 0.02° $h^{-1/2}$ ARW Accels: 3 μg bias stability, 0.02 (m s^{-1})/$h^{-1/2}$ VRW	7-9
GPS Receivers	1.5 m position accuracy	7-9
Integrated Units	0.002-5° pointing capability	7-9
Atomic Clocks	10 – 150 Frequency Range (MHz)	5-6
Deep Space Navigation	Bands: X, Ka, S, and UHF	7-9
Altimeters	~15 meters altitude, ~3 cm accuracy	7

5.2 State-of-the-Art – GNC Subsystems

5.2.1 Integrated Units

Integrated units combine multiple different attitude and navigation components to provide a simple, single-component solution to a spacecraft's GNC requirements. Typical components included are reaction wheels, magnetometer, magnetic torquers, and star trackers. The systems often include processors and software with attitude determination and control capabilities. Table 5-2 describes some of the integrated systems currently available. Blue Canyon Technologies' XACT (figure 5.1) flew on the NASA-led missions MarCO and ASTERIA, both of which were 6U platforms, and have also flown on 3U missions (MinXSS was deployed from NanoRacks in February 2016).

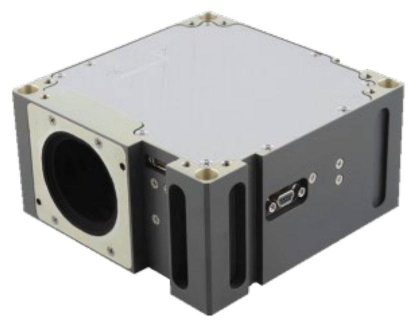

Figure 5.1: BCT XACT Integrated ADCS Unit. Credit: Blue Canyon Technologies.

Table 5-2: Currently Available Integrated Systems							
Manufacturer	**Model**	**Mass (kg)**	**Actuators**	**Sensors**	**Processor**	**Pointing Accuracy**	**TRL**
Arcsec	Arcus ADC	0.715	3 reaction wheels 3 magnetic torquers	1 star tracker 3 gyros 6 photodiodes 3 magnetometers	Yes	0.1°	7-9
Berlin Space Technologies	IADCS-100	0.4	3 reaction wheels 3 magnetic torquers	1 star tracker 3 gyros, 1 magnetometer, 1 accelerometer	Yes	<<1 deg	7
AAC Clyde Space	iADCS-200	0.470	3 reaction wheels 3 magnetic torquers	1 star tracker 1 IMU, Optionally high precision magnetometer and sun sensors	Yes	<1°	7-9
AAC Clyde Space	iADCS-400	1.7	3 reaction wheels 3 magnetorquers	1 star tracker, 1 IMU, Optionally high precision magnetometer and sun sensors	Yes	<1°	7-9
Blue Canyon Technologies	XACT-15	0.885	3 reaction wheels 3 magnetorquers	1 star tracker 3-axis magnetometer	Yes	0.003/0.007°	7-9
Blue Canyon Technologies	XACT-50	1.230	3 reaction wheels 3 magnetorquers	1 star tracker 3-axis magnetometer	Yes	0.003/0.007°	7-9
Blue Canyon Technologies	XACT-100	1.813	3 reaction wheels 3 magnetorquers	1 star tracker 3-axis magnetometer	Yes	0.003/0.007°	7-9

Blue Canyon Technologies	Flexcore	configuration dependent	3 – 4 reaction wheels 3 magnetorquers	2 star trackers 3-axis magnetometer	Yes	0.002°	7-9
CubeSpace Satellite Systems	CubeADCS 3-Axis Small	0.55	3 reaction wheels 3 magnetorquers	10 coarse sun sensors 2 fine sun/earth sensors 1 magnetometer	Yes	<1°	7-9
CubeSpace Satellite Systems	CubeADCS 3-Axis Small with Star Tracker	0.61	3 reaction wheels 3 magnetorquers	10 coarse sun sensors 2 fine sun/earth sensors 1 magnetometer 1 star tracker	Yes	<0.1°	7-9
CubeSpace Satellite Systems	CubeADCS 3-Axis Medium	0.79	3 reaction wheels 3 magnetorquers	10 coarse sun sensors 2 fine sun/earth sensors 1 magnetometer	Yes	<1°	7-9
CubeSpace Satellite Systems	CubeADCS 3-Axis Medium with Star Tracker	0.84	3 reaction wheels 3 magnetorquers	10 coarse sun sensors 2 fine sun/earth sensors 1 magnetometer 1 star tracker	Yes	<0.1°	7-9
CubeSpace Satellite Systems	CubeADCS 3-Axis Large	1.1	3 reaction wheels 3 magnetorquers	10 coarse sun sensors 2 fine sun/earth sensors 1 magnetometer	Yes	<1°	7-9
CubeSpace Satellite Systems	CubeADCS 3-Axis Large with Star Tracker	1.15	3 reaction wheels 3 magnetorquers	10 coarse sun sensors 2 fine sun/earth sensors 1 magnetometer 1 star tracker	Yes	<0.1°	7-9
CubeSpace Satellite Systems	CubeADCS Y-Momentum	0.3	1 momentum wheel 3 magnetic torquers	10 coarse sun sensors 1 magnetometer	Yes	<5°	7-9

5.2.2 Reaction Wheels

Miniaturized reaction wheels provide small spacecraft with a three-axis precision pointing capability. They must be carefully selected based on several factors including the mass of the spacecraft and the required rotation performance rates. Reaction wheels provide torque and momentum storage along the wheel spin axis which results in the spacecraft counter-rotating around the spacecraft center of mass due to conservation of angular momentum from the wheel spin direction. Table 5-3 lists a selection of high-heritage miniature reaction wheels. Except for three units, all the reaction wheels listed have spaceflight heritage. For full three-axis control, a spacecraft requires three wheels mounted orthogonally. However, a four-wheel configuration is often used to provide fault tolerance (6). Reaction wheels need to be periodically desaturated using an actuator that provides an external torque, such as thrusters or magnetic torquers (7).

In addition, the multiple reaction wheels are often assembled in a "skewed" or angled configuration such that there exists a cross-coupling of torques with two or more reaction wheels. While this reduces the torque performance in any single axis, it allows a redundant, albeit reduced, torque capability in more than one axis. The result is that should any single reaction wheel fail, one or more reaction wheels are available as a reduced-capability backup option.

Table 5-3: High Heritage Miniature Reaction Wheels

Manufacturer	Model	Mass (kg)	Peak Power (W)	Peak Torque (Nm)	Momentum Capacity (Nms)	# Wheels	Radiation Tolerance (krad)	TRL
Berlin Space Technologies	RWA05	1.700	0.5	0.016	0.0005	1	30	7-9
Blue Canyon Technologies	RWP015	0.130	1	0.004	0.015	1	Unk	7-9
Blue Canyon Technologies	RWP050	0.240	1	0.007	0.050	1	Unk	7-9
Blue Canyon Technologies	RWP100	0.330	1	0.007	0.100	1	Unk	7-9
Blue Canyon Technologies	RWP500	0.750	6	0.025	0.500	1	Unk	7-9
Blue Canyon Technologies	RW1	0.950	10	0.07	1.000	1	Unk	7-9
Blue Canyon Technologies	RW4	3.200	10	0.250	4.000	1	Unk	7-9
Blue Canyon Technologies	RW8	4.400	10	0.250	8.000	1	Unk	7-9
CubeSpace Satellite Systems	CubeWheel Small	0.060	0.65	0.00023	0.00177	1	24	7-9
CubeSpace Satellite Systems	CubeWheel Small+	0.090	2.3	0.0023	0.0036	1	24	7-9
CubeSpace Satellite Systems	CubeWheel	0.150	2.3	0.001	0.01082	1	24	7-9

	Medium							
CubeSpace Satellite Systems	CubeWheel Large	0.225	4.5	0.0023	0.03061	1	24	7-9
GomSpace	NanoTorque GSW-600	0.940	0.3	0.0015	0.019	1	Unk	Unk
Comat	RW20	0.180	1	0.002	0.02	1	Up to 20Krad*	7
Comat	RW40	0.230	1	0.004	0.04	1	Up to 20Krad*	8
Comat	RW60	0.275	1	0.006	0.06	1	Up to 20Krad*	7
AAC Clyde Space	RW210	0.48	0.8	0.0001	0.006	1	36	7-9
AAC Clyde Space	RW400	0.375	15	0.008	0.050	1	36	7-9
AAC Clyde Space	Trillian-1	1.5	24	47.1	1.2	1	Unk	
NanoAvionics	RWO	0.137	3.25	0.0032	0.020	1	20	7-9
NanoAvionics	4RWO	0.665	6	0.0059	0.037	4	20	7-9
NewSpace Systems	NRWA-T6	<5	136	0.3	0.00783	1	20	7-9
NewSpace Systems	NRWA-T065	1.55	1.7	0.02	0.00094	1	10	7-9
NewSpace Systems	NRWA-T2	2.8	0.4	0.09	0.00163	1	10	7-9
Rocket Lab	RW-0.03	0.185	1.8	0.002	0.040	1	20	7-9
Rocket Lab	RW-0.003	0.048	Unk	0.001	0.005	1	10	5-6
Rocket Lab	RW-0.01	0.122	1.05	0.001	0.018	1	20	7-9
Rocket Lab	RW3-0.06	0.235	23.4	0.020	0.180	1	20	7-9
Rocket Lab	RW4-0.2	0.6	Unk	0.1	0.2	1	60	7-9
Rocket Lab	RW4-0.4	0.77	Unk	0.1	0.4	1	60	7-9
Rocket Lab	RW4-1.0	1.38	43	0.1	1	1	60	7-9

Vectronic Aerospace	VRW-A-1	1.90	110	0.090	6.000	1	20	Unk
Vectronic Aerospace	VRW-B-2	1.00	45	0.020	0.200	1	20	Unk
Vectronic Aerospace	VRW-C-1	2.3	45	0.020	1.20	1	20	Unk
Vectronic Aerospace	VRW-D-2	2	65	0.05	2.0	1	20	Unk
Vectronic Aerospace	VRW-D-6	3	110	0.09	6	1	20	Unk

*Printed Circuit Board (PCB) level

5.2.3 Magnetic Torquers

Magnetic torquers provide control torques perpendicular to the local external magnetic field. Table 5-4 lists a selection of high heritage magnetic torquers and figure 5.3 illustrates some of ZARM Technik's product offerings. Magnetic torquers are often used to remove excess momentum from reaction wheels. As control torques can only be provided in the plane perpendicular to the local magnetic field, magnetic torquers alone cannot provide three-axis stabilization.

Figure 5.3: Magnetorquers for micro satellites. Credit: ZARM Technik.

Use of magnetic torquers beyond low-Earth orbit and in interplanetary applications need to be carefully investigated since their successful operation is relying on a significant local external magnetic field. This magnetic field may or may not be available in the location and environment for that mission and additional control methods may be required.

Table 5-4: High Heritage Magnetic Torquers

Manufacturer	Model	Mass (kg)	Power (W)	Peak Dipole (A m^2)	# Axes	Radiation Tolerance (krad)	TRL
CubeSpace Satellite Systems	CubeTorquer Small	0.028	0.42	0.24	1	24	7-9
CubeSpace Satellite Systems	CubeTorquer Medium	0.036	0.37	0.66	1	24	7-9

CubeSpace Satellite Systems	CubeTorquer Large	0.072	0.37	1.90	1	24	7-9
CubeSpace Satellite Systemse	CubeTorquer Coil(Single)	0.046	0.31	0.13	1	24	7-9
CubeSpace Satellite Systems	CubeTorquer Coil(Double)	0.074	0.64	0.27	1	24	7-9
GomSpace	Nano Torque GST-600	0.156	Unk	0.31 – 0.34	3	Unk	Unk
GomSpace	NanoTorque Z-axis Internal	0.106	Unk	0.139	1	Unk	Unk
ISISPACE	Magnetorquer Board	0.196	1.2	0.20	3	Unk	7-9
MEISEI	Magnetic Torque Actuator for Spacecraft	0.5	1	12	1	Unk	7-9
AAC Clyde Spce	MTQ800	0.395	3	15	1	Unk	7-9
NanoAvionics	MTQ3X	0.205	0.4	0.30	3	20	7-9
NewSpace Systems	NCTR-M003	0.030	0.25	0.29	1	Unk	7-9
NewSpace Systems	NCTR-M012	0.053	0.8	1.19	1	Unk	7-9
NewSpace Systems	NCTR-M016	0.053	1.2	1.6	1	Unk	7-9
Rocket Lab	TQ-40	0.825	Unk	48.00	1	Unk	7-9
Rocket Lab	TQ-15	0.400	Unk	19.00	1	Unk	7-9
ZARM Technik**	MT0.2-1	0.012-0.014	0.135-0.25	0.2	1	NA*	7-9
ZARM Technik	MT0.5-1	0.009	0.275	0.5	1	NA*	7-9
ZARM Technik	MT0.7-1-01	0.035	0.5	0.7	1	NA*	7-9
ZARM Technik	MT1-1-01	0.065	0.23	1	1	NA*	7-9
ZARM Technik	MT1.5-1-01	0.097	0.4	1.5	1	NA*	7-9
ZARM Technik	MT2-1-02	0.1	0.5	2	1	NA*	7-9
ZARM Technik	MT3-1-D22042701	0.15	0.7	3	1	NA*	7-9

ZARM Technik	MT4-1	0.15	0.6	4	1	NA*	7-9
ZARM Technik	MT5-1	0.19-0.3	0.73-0.75	5	1	NA*	7-9
ZARM Technik	MT5-2	0.31	0.77	5	1	NA*	7-9
ZARM Technik	MT6-2	0.25-0.3	0.48-1.1	6	1	NA*	7-9
ZARM Technik	MT7-2	0.4	0.9	7	1	NA*	7-9
ZARM Technik	MT10-1	0.35-0.4	0.53-0.8	10	1	NA*	7-9
ZARM Technik	MT10-2	0.37-0.48	0.7-1	10	1	NA*	7-9
ZARM Technik	MT15-1	0.4-0.55	1.0-1.55	15	1	NA*	7-9
ZARM Technik	MT15-2	0.5-0.55	0.9-1.5	15	1	NA*	7-9

* Only EEE parts are connector and wires. Magnetotorquer is not sensitive to ionizing radiation.
** ZARM Technik: Over 200 models available with design to mass/power optimization

5.2.4 Thrusters

Thrusters used for attitude control are described in Chapter 4: In-Space Propulsion. Pointing accuracy is determined by minimum impulse bit, and control authority by thruster force.

5.2.5 Star Trackers

A star tracker can provide an accurate estimate of the absolute three-axis attitude by comparing a digital image to an onboard star catalog (8). Star trackers identify and track multiple stars and provide three-axis attitude several times a second. Table 5-5 lists some models suitable for use on small spacecraft. For example, Arcsec's Sagitta Star Tracker was launched on the SIMBA cubesat in 2020.

Table 5-5: Star Trackers Suitable for Small Spacecraft								
Manufacturer	**Model**	**Mass (kg)**	**Power (W)**	**FOV**	**Cross axis accuracy (3s)**	**Twist accuracy (3s)**	**Radiation Tolerance (krad)**	**TRL**
Redwire Space	Star Tracker	0.475	2.5	14x19	10/27"	51"	75	7-9
Arcsec	Sagitta	0.275	1.4	25.4°	6	30	20	7-9
Arcsec	Twinkle	0.04	0.6	10.4°	30	180	Unk	7-9
Ball Aerospace	CT-2020	3.000	8	Unk	1.5"	1"	Unk	5-6
Berlin Space Technologies / AAC Clyde Space	ST200	0.040	0.65	22°	30"	200"	11	7-9
Berlin Space Technologies / AAC Clyde Space	ST400	0.250	0.75	15°	15"	150"	11	7-9
Blue Canyon Technologies	Standard NST	0.350	1.5	10° x 12°	6"	40"	Unk	7-9
Blue Canyon Technologies	Extended NST	1.300	1.5	10° x 12°	6"	40"	Unk	7-9
Creare	UST	0.840	Unk	Unk	7"	15"	Unk	5-6
CubeSpace Satellite Systems	CubeStar	0.055	0.264	58-47°	55.44" 0.02°	77.4	19	7-9
Danish Technical University	MicroASC	0.425	1.9	Unk	2”	Unk	Unk	7-9
Leonardo	Spacestar	1.600	6	20° x 20°	7.7"	10.6"	Unk	7-9
NanoAvionics	ST-1	0.108	1.2	21° full-cone	8"	50"	20	7-9
Rocket Lab	ST-16RT2	0.185	1	8° half-cone	5"	55"	Unk	7-9
Sodern	Auriga-CP	0.205	1.1	Unk	2"	11"	Unk	7-9

Sodern	Hydra-M	2.75	7	Unk	Unk	Unk	Unk	5-6
Sodern	Hydra-TC	5.3	8	Unk	Unk	Unk	Unk	5-6
Solar MEMS Technologies	STNS	0.14	1	12°	40"	70"	20	7-9
Space Micro	MIST	0.520	3	14.5°	15"	105"	30	7-9
Space Micro	μSTAR-100M	1.800	5	Unk	15"	105"	100	Unk
Space Micro	μSTAR-200M	2.100	8-10	Unk	15"	105"	100	Unk
Space Micro	μSTAR-200H	2.700	10	Unk	3"	21"	100	Unk
Space Micro	μSTAR-400M	3.300	18	Unk	15"	105"	100	Unk
Terma	T1	0.76	0.8	20° circular	2.2"	9"	100	5-6
Terma	T3	0.35	2	20° circular	2.6"	10"	8	5-6
Vectronic Aerospace	VST-41MN	0.7 - 0.9	2.5	14° x 14°	27"	183"	20	7-9
Vectronic Aerospace	VST-68M	0.470	3	14° x 14°	7.5"	45"	20	Unk

5.2.6 Magnetometers

Magnetometers provide a measurement of the local magnetic field which can be used to estimate 2-axis information about the attitude (9). Table 5-6 provides a summary of some three-axis magnetometers available for small spacecraft, one of which is illustrated in figure 5.4.

Figure 5.4: NSS Magnetometer. Credit: NewSpace Systems.

Table 5-6: Three-axis Magnetometers for Small Spacecraft

Manufacturer	Model	Mass (kg)	Power (W)	Resolution (nT)	Orthogonality	Radiation Tolerance (krad)	TRL
GomSpace	NanoSense M315	0.008	Unk	Unk	Unk	Unk	7-9
AAC Clyde Space	MM200	0.012	0.01	1.18	Unk	30	7-9
MEISEI	3-Axis Magnetometer for Small Satellite	0.220	1.5	Unk	1°	Unk	7-9
NewSpace Systems	NMRM-Bn25o485	0.085	0.75	8	1°	10	7-9
AAC Clyde Space	MAG-3	0.100	Voltage Dependent	Unk	1°	10	7-9
ZARM Technik	Analogue High-Rel Fluxgate Magnetometer FGM-A-75	0.33	0.75 W	±75000	1°	50	9
ZARM Technik	Digital AMR Magnetometer AMR-D-100-EFRS485	0.18	0.3 W	±100000	1°	unk	6-7

5.2.7 Sun Sensors

Sun sensors are used to estimate the direction of the Sun in a spacecraft body frame. Sun direction estimates can be used for attitude estimation, though to obtain a three-axis attitude estimate at least one additional independent source of attitude information is required (e.g., the Earth nadir vector or the direction to a star). Because the Sun is easily identifiable and extremely bright, Sun sensors are often used for fault detection and recovery. However, care must be taken to ensure the Moon or Earth's albedo is not inadvertently perturbing the measurement.

Figure 5.5: Redwire Coarse Sun Sensor Detector (Cosine Type). Credit: Redwire Space.

There are several types of Sun sensors which operate on different principles.

<u>Cosine detectors</u> are photocells. Their output is the current generated by the cell, which is (roughly) proportional to the cosine of the angle between the sensor boresight and the Sun. Typically several cosine detectors (pointing in different directions) are used on a spacecraft for full sky coverage. Cosine detectors (e.g., figure 5.5) are inexpensive, low-mass, simple and reliable devices, but their accuracy is typically limited to a few degrees, and they do require analog-to-digital converters.

<u>Quadrant detectors.</u> Quadrant sun sensors typically operate by shining sunlight through a square window onto a 2 x 2 array of photodiodes. The current generated by each photodiode is a function of the direction of the Sun relative to the sensor boresight. The measured currents from all four cells are then combined mathematically to produce the angles to the Sun.

<u>Digital Sun Sensor.</u> The Sun illuminates a narrow slit behind which, is located a geometric coded bit mask and a number of photodiodes under the mask. Depending on the angle to the Sun, the photodiodes will be illuminated as per the geometric pattern resulting in correpondingly different photocurrents which are then amplified and thresholded against an average value. Given the known slit geometries, this digital bit output can be then converted to a sun angle.

<u>Sun Camera.</u> Some sun sensors are build as a small camera imaging the Sun. Since the Sun is so bright, the optics will include elements to decrease the thoughput. A computer will identify the image of the Sun and calculate the centroid. Sun sensors can be made very accurate this way. Sometimes, multiple apertures are included to increase accuracy.

Examples of small spacecraft sun sensors are described in table 5-7.

Table 5-7: Small Spacecraft Sun Sensors										
Manufacturer	**Model**	**Sensor Type**	**Mass (kg)**	**Peak Power (W)**	**Analog or Digital**	**FOV**	**Accuracy (3s)**	**# Measurement Angles**	**Radiation Tolerance (krad)**	**TRL**
Redwire Space	Coarse Analog Sun Sensor	Coarse Analog Sun Sensor	0.045	0	Analog	±40° (Can be modified to meet specific FOV requirements)	±1°	1	>100	7-9
Redwire Space	Coarse Sun Sensor (Cosine Type)	Coarse Sun Sensor (Cosine Type)	0.010	0	Analog	APPROXIMAT E COSINE, CONICAL SYMMETRY	±2° to ±5°	Depends on configuration	>100	7-9
Redwire Space	Coarse Sun Sensor Pyramid	Coarse Sun Sensor Pyramid	0.13	0	Analog	2π STERADIAN PLUS	±1° to ±3°	2	>100	7-9
Redwire Space	DIGITAL SUN SENSOR (±32°)	DIGITAL SUN SENSOR (±32°)	Sensor 0.3 kg Electroni cs ~1	1	Digital	±32° x ±32° (each sensor)	±0.125°	2	100	7-9
Redwire Space	Digital Sun Sensor (±64°)	Digital Sun Sensor (±64°)	Sensor0 .25 Electroni cs 0.29 - 1.1	0.5	Digital	128° X 128° (EACH SENSOR) NOTE: 4π STERADIANS ACHIEVED WITH 5 SENSORS	±0.25°	2	100	7-9
Redwire Space	Fine Pointing Sun Sensor	Fine Pointing Sun Sensor	Sensor .95 Electroni cs 1.08	< 3	Digital	±4.25° x ±4.25° (Typical)	Better than ±0.01°	2	100	7-9

Redwire Space	Fine Spinning Sun Sensor (±64°)	Fine Spinning Sun Sensor (±64°)	Sensor 0.109 Electronics 0.475 – 0.725	0.5	Analog and Digital	±64° FAN SHAPED (each sensor)	±0.1°	1 plus Sun Pulse	100	7-9
Redwire Space	Micro Sun Sensor	Micro Sun Sensor	< 0.002	< 0.02	Analog	± 85° MINIMUM	±5°	2	Approx. 10	5-6
Redwire Space	Miniature Spinning Sun Sensor (±87.5°)	Miniature Spinning Sun Sensor (±87.5°)	< 0.25	0.5	Digital	±87.5° (FROM NORMAL TO SPIN AXIS)	±0.1°	1 plus Sun Pulse	100	7-9
Redwire Space	FINE SUN SENSOR (±50°)	FINE SUN SENSOR (±50°)	Unk	Unk	Digital	100 X 100 Each Sensor	±0.01° TO ±0.05°	2	100, 150, or 300	7-9
Bradford Space	CoSS	Cosine	0.024	0	Analog	160° full cone	3°	1	40000	7-9
Bradford Space	CoSS-R	Cosine	0.015	0	Analog	180° full cone	3°	1	120000	7-9
Bradford Space	CSS-01, CSS-02 Only shows one CSS	Cosine	0.215	0	Analog	180° full cone	1.5°	2	70000	7-9
Bradford Space	FSS	Quadrant	0.375	0.25	Analog	128° x 128°	0.3°	2	100	7-9
Bradford Space	Mini-FSS	Quadrant	0.050	0	Analog	128° x 128°	0.2° With on-board implementation	2	20000	7-9
CubeSpace Satellite Systems	CubeSense	Camera	0.030	<0.2	Digital	180°	0.2°	2	24	7-9
GomSpace	NanoSense FSS	Quadrant	0.002	Unk	Digital	{45°, 60°}	{±0.5°, ±2°}	2	Unk	Unk

AAC Clyde Space	SS200	Unk	.003	0.04	Digital	110°	<1°	Unk	>36	7-9
Lens R&D	BiSon64-ET	Quadrant	0.023	0	Analog	±58° per axis	0.5°	2	9200	9
Lens R&D	BiSon64-ET-B	Quadrant	0.033	0	Analog	±58° per axis	0.5°	2	9200	8
Lens R&D	MAUS	Quadrant	0.014	0	Analog	±57° per axis	0.5°	2	9200	7-9
NewSpace Systems	NFSS-411	Unk	0.035	0.150	Digital	140°	0.1°	TBD	20	9
NewSpace Systems	NCSS-SA05	Unk	0.005	0.05	Analog	114°	0.5°	TBD	Unk	9
Solar MEMS Technologies	nanoSSOC-A60	Orthogonal	0.004	0.007	Analog	±60° per axis	0.5°	2	100	7-9
Solar MEMS Technologies	nanoSSOC-D60	Orthogonal	0.007	0.076	Digital	±60° per axis	0.5°	2	30	7-9
Solar MEMS Technologies	SSOC-A60	Orthogonal	0.025	0.01	Analog	±60° per axis	0.5°	2	100	7-9
Solar MEMS Technologies	SSOC-D60	Orthogonal	0.035	0.315	Digital	±60° per axis	0.5°	2	30	7-9
Solar MEMS Technologies	ACSS	Quadrant & Redundant	0.035	0.072	Analog	±60° per axis	0.5°	2	200	7-9
Space Micro	CSS-01, CSS-02	Cosine	0.010	0	Analog	120° full cone	5°	1	100	7-9
Space Micro	MSS-01	Quadrant	0.036	0	Analog	48° full cone	1°	2	100	7-9

5.2.8 Horizon Sensors

Horizon sensors can be simple infrared horizon crossing indicators (HCI), or more advanced thermopile sensors that can detect temperature differences between the poles and equator. For terrestrial applications, these sensors are referred to as Earth Sensors, but can be used for other planets. Examples of such technologies are described in table 5-8 and illustrated in figure 5.6.

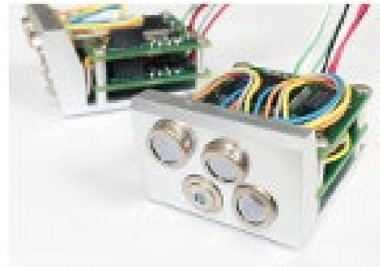

Figure 5.6: MAI-SES. Credit: Redwire Space.

In addition to the commercially-available sensors listed in table 5-8, there has been some recent academic interest in horizon sensors for CubeSats with promising results (24) (10) (11).

Table 5-8: Commercially Available Horizon Sensors

Manufacturer	Model	Sensor Type	Mass (kg)	Peak Power (W)	Analog or Digital	Accuracy	# Measurement Angles	Rad Tolerance (krad)	TRL
CubeSpace Satellite Systems	CubeSense	Camera	0.030	0.200	Digital	0.2°	2	24	7-9
Servo	Mini Digital HCI	Pyroelectric	0.050	Voltage Dependent	Digital	0.75°	Unk	Unk	7-9
Servo	RH 310 HCI	Pyroelectric	1.5	1	Unk	0.015°	Unk	20	Unk
SITAEL	Digital Earth Sensor	Microbolometer	0.4	<2	Digital	<1°	Unk	Unk	Unk
Solar MEMS Technologies	HSNS	Infrared	0.120	0.150	Digital	1°	2	30	7-9

5.2.9 Inertial Sensing

Inertial sensors include gyroscopes for measuring angular change and accelerometers for measuring velocity change. They are packaged in different ways that range from single-axis devices (i.e., a single gyroscope or accelerometer), to packages which include 3 orthogonal axes of gyroscopes (Inertial Reference Unit (IRU)) to units containing 3 orthogonal gyros and 3 orthogonal accelerometers (Inertial Measurement Unit (IMU)). These sensors are frequently used to propagate the vehicle state between measurement updates of a non-inertial sensor. For example, star trackers typically provide attitude updates at a few Hertz. If the control system requires accurate knowledge between star tracker updates, then an IMU may be used for attitude propagation between star tracker updates.

Gyroscope technologies typically used in modern small spacecraft are fiber optic gyros (FOGs) and MEMS gyros, with FOGs usually offering superior performance at a mass and cost penalty (12). Other gyroscope types exist (e.g., resonator gyros, ring laser gyros), but these are not common in the SmallSat/CubeSat world due to size, weight, and power (SWaP) and cost considerations.

Gyro behavior is a complex topic (13) and gyro performance is typically characterized by a multitude of parameters. Table 5-9 only includes bias stability and angle random walk for gyros, and bias stability and velocity random walk for accelerometers, as these are often the driving performance parameters. That said, when selecting inertial sensors, it is important to consider other factors such as dynamic range, output resolution, bias, sample rate, etc.

Table 5-9: Gyros Available for Small Spacecraft

Manufacturer	Model	Sensor Type	Technology	Mass (kg)	Power (W)	Gyros				Accelerometers			
							Bias Stability		ARW		Bias Stability		VRW
						# Axes	(°/hr)	stat	(°/rt(hr))	# Axes	(µg)	stat	(m/sec)/rt(hr)
Emcore	QRS11	Gyro	MEMS	≤0.06	0.8	1	6	Typical	N/A	N/A	N/A	N/A	N/A
Emcore	QRS28	Gyro	MEMS	≤0.025	0.5	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Honeywell	MIMU	IMU	RLG	4	34	3	0.05	Unk	0.01	Unk	100	Unk	Unk
Honeywell	HG1700	IMU	RLG	0.9	5.000	3	1.000	1σ	0.125	3	1000	1σ	0.65
L3	CIRUS	Gyros	FOG	15.400	40.000	3	0.000	1σ	0.100	0	N/A	Unk	N/A
NewSpace Systems	NSGY-001	IRU	Image-based rotation estimate	0.055	0.200	3	N/A		N/A	0	N/A	Unk	N/A
Northrop Grumman	LN-200S	IMU	FOG, SiAc	0.748	12	3	1.000	1σ	0.070	3	300	1σ	Unk
NovAtel	OEM-IMU-STIM300	IMU	MEMS	0.055	1.50	3	0.500	TBD	0.150	3	50	TBD	0.060
Safran	STIM202	IRU	MEMS	0.055	1.500	3	0.400	TBD	0.170	0	N/A	TBD	N/A

Safran	STIM210	IRU	MEMS	0.052	1.500	3	0.300	TBD	0.150	0	N/A	TBD	N/A
Safran	STIM300	IMU	MEMS	0.055	2.000	3	0.300	TBD	0.150	3	50	TBD	0.07
Safran	STIM318	IMU	MEMS	0.057	2.500	3	0.300	TBD	0.150	3	3	TBD	0.015
Safran	STIM320	IMU	MEMS	0.057	2.500	3	0.300	TBD	0.100	3	3	TBD	0.015
Safran	STIM277H	IRU	MEMS	0.052	1.500	3	0.300	TBD	0.150	0	N/A	TBD	N/A
Safran	STIM377H	IMU	MEMS	0.055	2.000	3	0.300	TBD	0.150	3	50	TBD	0.07
Silicon Sensing Systems	CRH03	Gyro	MEMS	0.42	0.2 W	1	CRH03-010 – 0.03 CRH03-025 – 0.04 CRH03-100 – 0.04 CRH03-200 – 0.05 CRH03-400 – 0.1		CRH03-010 – 0.005 CRH03-025 – 0.006 CRH03-100 – 0.006 CRH03-200 – 0.008 CRH03-400 – 0.010	0	N/A	-	N/A
Silicon Sensing	CRH03 (OEM)	Gyro	MEMS	0.18	0.2 W	1	CRH03-010 – 0.03		CRH03-010 – 0.005	0	N/A	-	N/A

Systems							CRH03-025 – 0.04 CRH03-100 – 0.04 CRH03-200 – 0.05 CRH03-400 – 0.1		CRH03-025 – 0.006 CRH03-100 – 0.006 CRH03-200 – 0.008 CRH03-400 – 0.010				
Silicon Sensing Systems	RPU30	Gyro	MEMS	1.35	<0.8W	3	0.06		0.006	0	N/A	-	N/A
Silicon Sensing Systems	DMU41	9 DoF IMU	MEMS	<2	<1.5W	3	0.1		0.015	3	15	-	0.05
Silicon Sensing Systems	CAS	Acc	MEMS	0.004	Unk	0	N/A		N/A	2	CAS2X1S - 7.5 CAS2X2S - 7.5 CAS2X3S - 7.5 CAS2X4S - 25 CAS2X5S - 75		CAS2X1S - TBC CAS2X2S - TBC CAS2X3S - TBC CAS2X4S - TBC CAS2X5S - TBC
Vector Nav	VN-100*	IMU + magnetometers	MEMS	0.015	0.220	3	10.000	max	0.210	3	40	max	0.082

		+barom eter											
Vector Nav	VN-110*	IMU + magnet ometers	MEMS	0.12 5	2.5 00	3	1.000	ma x	0.0833	3	10	m ax	0.024

*Small form-factor versions of these products available.

5.2.10 GPS Receivers

For low-Earth orbit spacecraft, GPS receivers are now the primary method for performing orbit determination, replacing ground-based tracking methods. Onboard GPS receivers are now considered a mature technology for small spacecraft, and some examples are described in table 5-10. There are also next-generation chip-size COTS GPS solutions, for example the NovaTel OEM 719 board has replaced the ubiquitous OEMV1.

GPS accuracy is limited by propagation variance through the exosphere and the underlying precision of the civilian use C/A code (14). GPS units are controlled under the Export Administration Regulations (EAR) and must be licensed to remove Coordinating Committee for Multilateral Export Control (COCOM) limits (15).

Although the usability of GPS is limited to LEO missions, past experiments have demonstrated the ability of using a weak GPS signal at GSO, and potentially soon to cislunar distances (16) (17). Development and testing in this fast-growing area of research and development may soon make onboard GPS receivers more commonly available.

Table 5-10: GPS Receivers for Small Spacecraft

Manufacturer	Model	Mass (kg)	Power (W)	Accuracy (m)	Radiation Tolerance (krad)	TRL
APL	Frontier Radio Lite	0.4	1.4	15	20	5-6
General Dynamics	Explorer	1.2	8	15	Unk	7-9
General Dynamics	Viceroy-4	1.1	8	15	Unk	7-9
SkyFox Labs	piNAV-NG	0.024	0.124	10	30	7-9
Surrey Satellite Technology	SGR-Ligo	0.09	0.5	5	5	7-9
GomSpace	GPS-kit	0.031	1.3	1.5	Unk	Unk
Spacemanic	Celeste_gnss_rx	0.025	~0.1	1.5	40	7-9
AAC Clyde Space	GNSS-701	0.16	Unk	<5	10	7-9
Syrlinks	GPS (L1/L5) GALILEO (E1/E5/E6) BeiDou (B1/B3)	0.435	Unk	<0.1	15	5-6

5.2.11 Deep Space Navigation

In deep space, navigation is performed using radio transponders in conjunction with the Deep Space Network (DSN). As of 2020, the only deep space transponder with flight heritage suitable for small spacecraft was the JPL-designed and General Dynamics-manufactured Small Deep Space Transponder (SDST). JPL has also designed IRIS V2, which is a deep space transponder that is more suitable for the CubeSat form factor. Table 5-11 details these two radios, and the SDST is illustrated in figure 5.7. IRIS V2, derived from the Low Mass Radio Science Transponder (LMRST), flew on the MarCO CubeSats and is scheduled to fly on INSPIRE (18) and was selected for seven Artemis I secondary payloads slated for launch end of 2022 (27).

Figure 5.7: General Dynamics SDST. Credit: General Dynamics.

Table 5-11: Deep Space Transponders for Small Spacecraft

Manufacturer	Model	Mass (kg)	Power (W)	Bands	Radiation Tolerance (krad)	TRL
General Dynamics	SDST	3.2	12.5	X, Ka	50	7-9
Space Dynamics Laboratory	IRIS V2.1	1.1	35	X, Ka, S, UHF	15	7-9

5.2.12 Atomic Clocks

Atomic clocks have been used on larger spacecraft in low-Earth orbit for several years now, however integrating them on small spacecraft is relatively new. Table 5-12 provides examples of commercially available atomic clocks and oscillators for SmallSats. The conventional method for spacecraft navigation is a two-way tracking system of ground-based antennas and atomic clocks. The time difference from a ground station sending a signal and the spacecraft receiving the response can be used to determine the spacecraft's location, velocity, and (using multiple signals) the flight path. This is not a very efficient process, as the spacecraft must wait for navigation commands from the ground station instead of making real-time decisions, and the ground station can only track one spacecraft at a time, as it must wait for the spacecraft to return a signal (19). In deep space navigation, the distances are much greater from the ground station to spacecraft, and the accuracy of the radio signals needs to be measured within a few nanoseconds.

More small spacecraft designers are developing their own version of atomic clocks and oscillators that are stable and properly synchronized for use in space. They are designed to fit small spacecraft, for missions that are power- and volume-limited or require multiple radios.

Table 5-12: Atomic Clocks and Oscillators for Small Spacecraft							
Manufacturer	**Model**	**Dimensions (mm)**	**Mass (kg)**	**Power (W)**	**Frequency Range**	**Rad Tolerance**	**TRL**
AccuBeat	Ultra Stable Oscillator	131 x 120 x 105	2	6.5 W	57.51852 MHz	50	7-9
Bliley Technologies	Iris Series 1"x1" OCXO for LEO	19 x 11 x 19	0.016	1.5	10 MHz to 100 MHz	39	7-9
Bliley Technologies	Aether Series TCVCXO for LEO	21 x 14 x 8	Unk	0.056	10MHz to 150 MHz	37	Unk
Microsemi	Space Chip Scale Atomic Clock (CSAC)	41 x 36 x 12	0.035	0.12	10 MHz	20	5-6

5.2.13 LiDAR

Light Detection and Ranging (LiDAR) is new type of sensor that is emerging. The technology has matured in terrestrial applications (such as automotive applications) over the last decade and is used in larger spacecraft that are capable of proximity operations, like Orion. This sensor type has applications for small spacecraft altimetry and relative navigation (e.g., a Mars helicopter, rendezvous and docking, and formation flying). Table 5-13 lists examples of flown LiDARs.

Table 5-13: Lidar for Small Spacecraft						
Manufacturer	**Model**	**Mass (kg)**	**Power (W)**	**Max Range (m)**	**Radiation Tolerance (krad)**	**TRL**
Garmin	Lidar Lite V3	0.022	0.7	40	Unk	5-6*
ASC	GSFL-4K (3D)	3	30	>1 km in altimeter mode	Unk	7-9

*Specific units were qualified for Mars Ingenuity helicopter. Product line in general is not space qualified.

5.3 On the Horizon

Figure 5.8: High-speed magnetically levitated reaction wheel. Credit: Celeroton AG.

In general, technological progress in guidance, navigation, and control is advancing quickly in automotive research areas but is lagging slightly in the aerospace industry. Given the high maturity of existing GNC components, future developments in GNC are mostly focused on incremental or evolutionary improvements, such as decreases in mass and power, and increases in longevity and/or accuracy. This is especially true for GNC components designed for deep space missions that have only very recently been considered for small spacecraft. However, in a collaborative effort between the Swiss Federal Institute of Technology and Celeroton, there is progress being made on a high-speed magnetically levitated reaction wheel for small satellites (figure 5.8). The idea is to eliminate mechanical wear and stiction by using magnetic bearings rather than ball bearings. The reaction wheel implements a dual hetero/homopolar, slotless, self-bearing, permanent-magnet synchronous motor (PMSM). The fully active, Lorentz-type magnetic bearing consists of a heteropolar self-bearing motor that applies motor torque and radial forces on one side of the rotor's axis, and a homopolar machine that exerts axial and radial forces to allow active control of all six degrees of freedom. It can store 0.01 Nm of momentum at a maximum of 30,000 rpm, applying a maximum torque of 0.01 Nm (21)

Several projects funded via NASA's Small Spacecraft Technology (SST) program through the Smallsat Technology Partnerships (STP) initiative have began advancing GNC systems. Listed below in table 5-14 are projects that focused on GNC advancement, and further information can be found at the STP website:

https://www.nasa.gov/directorates/spacetech/small_spacecraft/smallsat-technology-partnership-initiative

Each presentation is from the STP Technology Exposition that was held in May 2021 and June 2022.

Table 5-14: STP Initiative GNC Projects

Project	University	Current Status	Reference
On-Orbit Demonstration of Surface Feature-Based Navigation and Timing	University of Texas, Austin	Still in development	STP Technology Expo presentation
Autonomous Nanosatellite Swarming (ANS) using Radio Frequency and Optical Navigation	Stanford University	Flying on Starling mission (expected launch early 2023)	STP Technology Expo presentation
Distributed multi-GNSS Timing and Localization (DiGiTaL)	Stanford University	Leveraged technology in Starling mission	STP Technology Expo presentation
Mems Reaction Control and Maneuvering for Picosat beyond LEO	Purdue University	Awarded a suborbital flight test through NASA's Flight Opportunities program	(29)

A Small Satellite Lunar Communications and Navigation System	University of Boulder, Colorado	Still in development	STP Technology Expo presentation
A high-precision continuous-time PNT compact module for the LunaNet small spacecraft	University of California, Los Angeles	Still in development	STP Technology Expo presentation

5.4 Summary

Conventional small spacecraft GNC technology is a mature area, with many high TRL components previously flown around Earth offered by several different vendors. These GNC techniques are generally semi/non-autonomous as on-board observations are collected with the assistance of ground-based intervention. As the interest for deep space exploration with small spacecraft grows, semi-to-fully autonomous navigation methods must advance. It is likely that future deep space navigation will rely solely on fully autonomous GNC methods that require zero ground-based intervention to collect/provide navigation data. This is a desirable capability as the spacecraft's dependence on Earth-based tracking resources (such as DSN) is reduced and the demand for navigation accuracy increases at large distances from Earth. However, current methods advancing deep space navigation involve both ground- and space-based tracking in conjunction with optical navigation techniques. To support this maturity, the small spacecraft industry has seen a spike in position, navigation, and timing (PNT) technology progression in inertial sensors and atomic clocks, and magnetic navigation for near-Earth environments.

Other GNC advances involve research on SmallSats performing on-orbit proximity operations. Several research papers have discussed ways to accomplish this, and previous extravehicular free flyers have demonstrated this innovative capability in the past few decades. The CubeSat Proximity Operations Demonstration (CPOD) project is the most recent CubeSat mission to validate and characterize low-power proximity operations technologies. Launched in May 2022, CPOD will demonstrate the ability of two 3U CubeSats to remain at determined points relative to each other, as well as precision circumnavigation and docking. This mission aims to advance technologies for nanosatellite attitude determination, navigation and control systems, in addition to demonstrating relative navigation capabilities (28). Seeker, a 3U CubeSat that was deployed September 2019, was built to demonstrate safe operations around a target spacecraft with core inspection capabilities. While Seeker was unable to perform its underlining goal, there were still several benefits for improving future missions (29).

The rising popularity of SmallSats in general, and CubeSats in particular, means there is a high demand for components, and engineers are often faced with prohibitive prices. The Space Systems Design Studio at Cornell University is tackling this issue for GNC with their PAN nanosatellites. A paper by Choueiri et al. outlines an inexpensive and easy-to-assemble solution for keeping the ADCS system below $2,500 (22). Lowering the cost of components holds exciting implications for the future and will likely lead to a burgeoning of the SmallSat industry.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

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