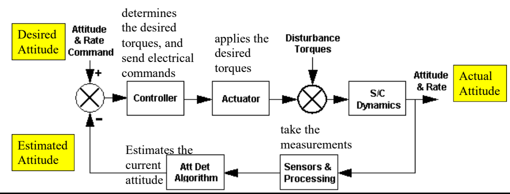
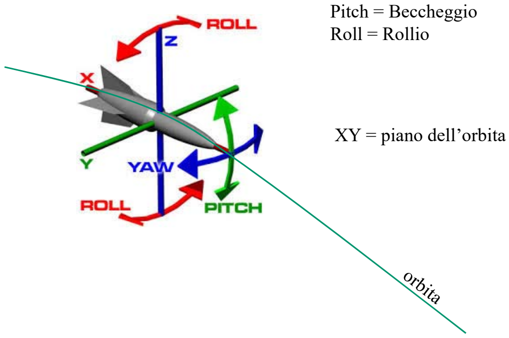
Attitude Determination and Attitude Control

- Placing the telescope in orbit is not the end of the story.
- It is necessary to point the telescope towards the selected targets, or to scan the selected sky area with the telescope.
- So the satellite attitude needs to be measured and controlled.

Attitude Control

- Is the control of the angular position and rotation of the spacecraft, either relative to the object that it is orbiting (Earth, Moon ..), or relative to the celestial sphere.
- The attitude control system (ACS) is composed of : *Attitude Sensors, Controller, Actuators.*





Yaw = Imbardata
Pitch = Beccheggio
Roll = Rollio

XY = piano dell'orbita

ACS: Gravity Gradient

Description:
Uses the change in gravity with altitude to create a torque when the principal axes are not aligned with the orbital reference frame. Long booms are usually extended to create the torque. The gravity gradient provides the restoring or stabilizing torque but does not damp the librational motion. Viscous dampers are added to dissipate the energy and damp out the librations. The gravity gradient torque can be a control torque but it can also be a disturbance torque if there are products of inertia. For example, LANDSAT had large products of inertia and the gravity gradient was the dominant disturbance torque.

Advantages:
Simple, reliable, cheap, long lifetime.

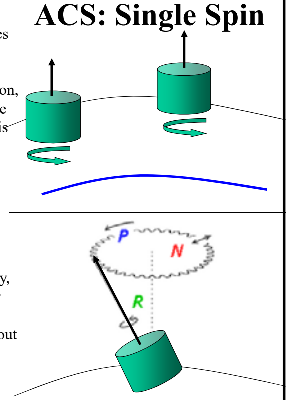
Disadvantages:
Poor pointing accuracy (5 deg), poor yaw control, thermal bending of boom causes oscillations, tendency to flip upside down.

(from D. Mortari)

ACS: Single Spin

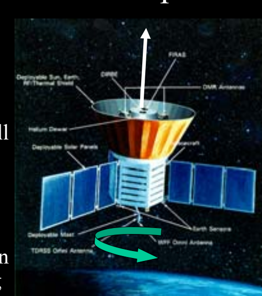
Description:
The entire spacecraft spins, which provides inertial orientation. The spinning provides gyroscopic stiffness, and stability.
The nutation damper damps out the nutation, but precession still exists. Spin is about the axis of maximum moment of inertia, that is usually, but not always, the orbit normal.
Solar arrays are fixed to the body.
Advantages:
Simple, reliable, long lifetime.
Disadvantages:
Sensor collection is limited to scanning obtained by spin motion. High angular momentum results in poor maneuverability, i.e., reorientation of spin axis. Poor power efficiency, only half the solar cells are illuminated at any one time. Must spin about the axis of maximum moment of inertia.

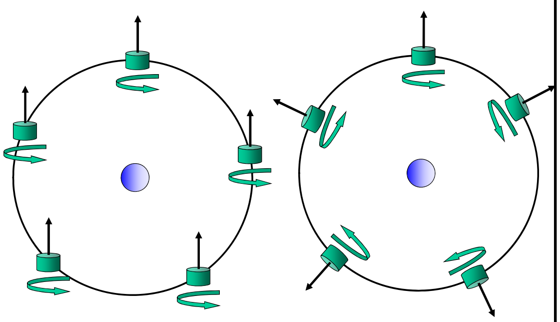
(from D. Mortari)



Spinning Satellites Examples

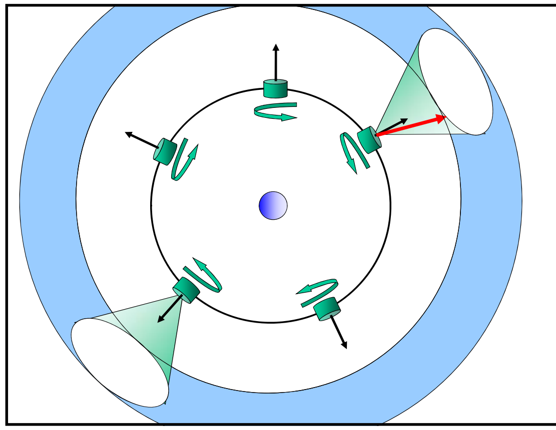
- Spinning is used in satellites for astronomy when sky scanning is required.
- COBE, WMAP, Planck all spin at 1-10 rpm, so the telescopes (antennas) can scan the sky at a rate of deg/s.
- Complex scan patterns can be obtained by combining satellite spin and slow re-orientation manouvers (see COBE, WMAP, Planck)

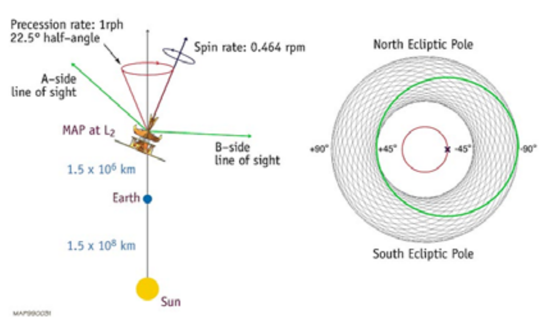




Flat spin: in the absence of perturbations the spin axis orientation remains constant with respect to the inertial frame of distant stars – Not useful for astronomy.

Using the ACS and perturbations, the spin axis orientation can be continuously reoriented away from the earth center. This is useful for full-sky surveys (COBE)

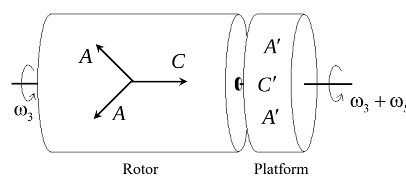




Dual-Spin Satellite (2/6)

A vehicle consisting of two primary components free to perform relative rotations about a common bearing axis is called a "dual- spin" vehicle, and the idea of stabilizing such a vehicle by spinning one part (the "rotor") while the other part (the "despun platform") rotates more slowly - or not at all - is called the dual-spin attitude stabilization concept.

This dual-spin configuration thus serves to create a spin stabilized satellite.



ACS: Dual Spin

Description:

The limitations of single spin satellites are partially overcome with dual spin satellites. With a dual spin satellite the payload, e.g. the antenna, is despun while the other portion of spacecraft spins to provide gyroscopic stability. Nutation is damped by nutation damper, located on either the spun or despun portion. Many of the geosynchronous communication satellites have been dual spin.

Advantages:
Despun payload allows Earth pointing payload. Can have spin about minimum moment of inertia axis. Reliable, long lifetime.

Disadvantages:
Poor power efficiency because solar cells are on spinning portion. High angular momentum results in poor maneuverability, i.e., reorientation of spin axis. Sensitive to mass imbalances.

(from D. Mortari)

ACS: Momentum Bias

Description: The momentum bias satellite is a variation of the dual spin concept that overcomes some of the problems of the dual spin. With the momentum bias spacecraft the gyroscopic stability is provided by a *rapidly spinning momentum wheel* rather than the bus. The payload and bus are despun or rotating at orbital rate. The momentum wheel provides control about the spin (pitch) axis and some combination of nutation damper, magnetic torquing, or propellant provide control about the yaw and roll axes. Use of propellant is avoided whenever possible. Magnetic or propellant are used for momentum damping.

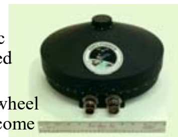
Advantages: Better pointing accuracy, better power efficiency due to despun solar arrays. Still relatively cheap and not complex which means less weight than three axis systems. When the pointing requirements are not stringent, i.e., > 0.5 deg, the momentum bias ACS is usually the desired approach. The momentum bias approach with magnetic torquers is the dominant type of ACS in LEO.

Disadvantages: Usually poor yaw control. Gyroscopic stiffness results in poor maneuverability. Poorer reliability and lifetime. Due to its lower cost and complexity and relatively accurate pointing capability this has been the most popular type of ACS.

(from D. Mortari)

Reaction (momentum) wheels

- Typically a spacecraft will have several momentum wheels oriented along orthogonal axes.
- To change its rotation along those axes it will increase or decrease the spin of the momentum wheels in the opposite direction. When the spacecraft achieves its desired orientation, it can then halt its rotation by braking the momentum wheels by the same amount.
- Momentum wheels are usually spun by electric motors. Both spin-up and braking are controlled electronically by computer controls.
- The strength of the materials of a momentum wheel establishes a speed at which the wheel would come apart, and therefore how much angular momentum it can store.
- Since the momentum wheel is a small fraction of the spacecraft's total inertia, easily-measurable changes in its speed provide very precise changes in angle.



Example:

- In the CNES ACS:
- Three magnetic-bearing reaction wheels apply a torque on the satellite to rotate it about one of its three axes.
- Two magnetic torquers interact with the Earth's magnetic field to generate torques and thus control the speed of rotation of the reaction wheels.
- Thrusters complete the system.

ACS: Three Axis

Description:

All three axes are independently controlled by mass expulsion, reaction wheels (RWs) or control moment gyros (CMGs). Usually RWs or CMGs are used for control and propellant (sometimes magnetic torquing) is used for momentum dumping.

Advantages:

Pointing accuracy, maneuverability and adaptability to changing mission requirements.

Disadvantages:

Cost, weight, complexity and lifetime.

(from D. Mortari)

ACS methods:

Passive	Semi-passive	Active
Gravity gradient	Momentum bias with magnetics	Propellant
Spinner with nutation damper	Reaction wheels with magnetics for momentum dumping	Reaction wheels with propellant for momentum dumping
Dual spinner with nutation damper	CMGs with magnetics for momentum dumping	CMGs with propellant for momentum dumping

(from D. Mortari)

Attitude Control Methods and their Capabilities

Type	Pointing Options	Manueverability		Accuracy	Lifetime Limits
		Translation	Rotation		
Passive					
• Gravity gradient	• Earth local vertical only	• Minor adjustments with thrusters	• Very limited	• ±5° (two axes)	• None
• Gravity gradient & momentum bias wheel	• Earth local vertical only	• Minor adjustments with thrusters	• Very limited	• ±5° (three axes)	• Life of wheel bearings
Spinners					
• Pure spinner	• Inertially fixed any direction • Repoint with precession maneuvers	• Large _V along spin axis, minor adjust in other two axes with thrusters	• High propellant usage to move stiff momentum vector • Momentum vector same as above	• ±0.3017° to ±1° in two axes (proportional to spin rate)	• Thruster propellant
• Dual spin	• Limited only by articulation on despun platform	• Large _V along spin axis, minor adjust in other two axes with thrusters	• Despun platform constrained by its own geometry	• Same as above for spin section • Despun dictated by payload reference & pointing	• Thruster propellant (if applies) • Despin bearings
3-axis stabilized					
• Zero momentum (3 wheels &thrusters)	• No constraints	• Any direction,any level depending on size of thruster and main engine	• No constraints (1)	• 0.001° to 1° depending on sensor & actuator selection	• Propellant • Life of sensor bearings
• Bias momentum (1wheel & roll thrusters)	• Best suited for local vertical pointing	• Same as zero momentum with full set of thrusters; otherwise, not suited to translation	• Momentum vector of the bias wheel prefers to stay normal to orbit plane, constraining yaw maneuver	• Depends on sensors but generally less accurate than zero momentum; e.g., 0.1° to 1°	• Propellant • Life of sensor bearings

(1) High rates with thrusters or control moment gyros; low rate, accurate control with reaction wheels.

Actuators

Actuators are usually broken into four classes: mass expulsion, momentum exchange, environmental and dissipative. An ACS may have actuators from any or all the classes.

Mass Expulsion	Momentum Exc.	Environmental	Dissipative
	Reaction wheel	Gravity gradient	Nutation damper
	Momentum wheel	Magnetic	GG viscous damper
	CMG	Aerodynamic	

There are two types of magnetic torquers. Those used for momentum dumping or control in momentum bias systems, and the eddy current dampers used in gravity gradient systems.

Range of torques available from some of these actuators (From Chobotov)

Actuator Type	Torque Range (N-m)
Reaction Control (RCS)	10^{-2} -10
Magnetic Torquer	10^{-2} -10^{-1}
Gravity Gradient	10^{-6} - 10^{-3}
Aerodynamic	10^{-5} - 10^{-3}
Reaction Wheel	10^{-1} - 1
Control Moment Gyro	10^{-2} - 10^{3}

From this table we see that RWs and CMGs are used when precision pointing and/or high torque is required. Satellites that perform rapid attitude maneuvers or have articulating payloads which create large disturbance torques require CMGs

Sensors

The types of sensors used for attitude determination are:

1. horizon sensors (or conical Earth scanners),
2. sun sensors,
3. star sensors,
4. magnetometers,
5. inertial reference units (Inertia Measurement Unit or attitude reference units ARU), and
6. GPS receivers.

Horizon sensors measure pitch and roll to an accuracy of about 0.1-0.5 deg. An accuracy less than 0.05 deg can be achieved by extensive calibration and accounting for the equatorial bulge. Sun and star sensors provide directions. An horizon sensor does not provide yaw information (for momentum bias systems it is not necessary to measure yaw). One wide-FOV or two narrow-FOV star sensors are needed to provide attitude. Since the star sensors cannot provide continuous attitude measurements an IMU/ARU is needed to provide the attitude between measurements. IMUs suffer from drift and biases and need frequent updates which are provided by the star sensors. Magnetometers measure Earth's magnetic. Accuracies no better than 1 deg can be obtained. The GPS receivers are used in an interferometer mode to determine attitude. Accuracies as good as 0.01 deg are expected using GPS.

Sun Sensors

Most common because they are light weight, not expensive, limited power required and because they provide an accuracy which is acceptable for most of the missions.

Sun is the principal source of energy (exemption: interplanetary spacecraft). Solar flux goes as $1/r^2$.

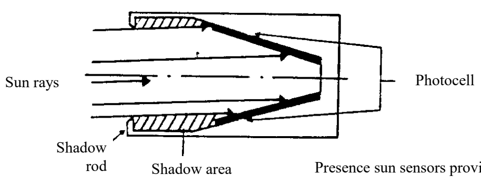
Sun (in the Inertial Reference Frame) is evaluated by using interpolating functions (armonic series expansion) which least square fit the Sun positions recorded in the star atlas.

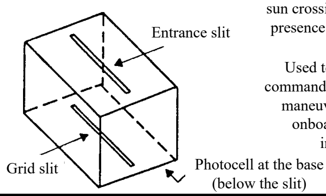
They are used to synchronize command with spin period, and they are used to protect star sensors.

At 1AU the sun may be considered as a point (0.267 deg.).

For GEO there is the parallax error (0.03 deg as max values).

Presence Sun Sensors





Presence sun sensors provide the sun crossing time only, or the sun presence within the sensor FOV

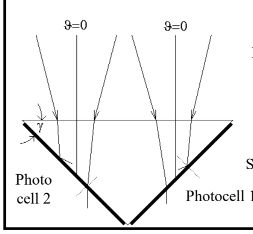
Used to synchronize pulsed command (spin-up, spin-down) to maneuvre, and to turn on/off onboard experiments and instrumentation.

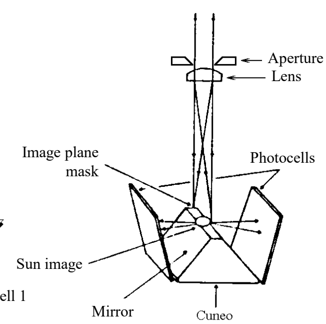
Presence Sun Sensors

Based on the Snell refraction law.

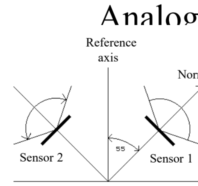
$$n \sin \vartheta = \sin \vartheta'$$

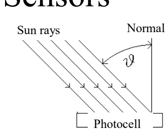
$$n \sin \gamma = 1$$



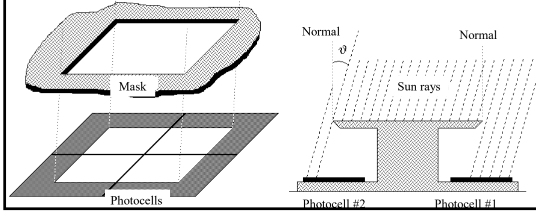


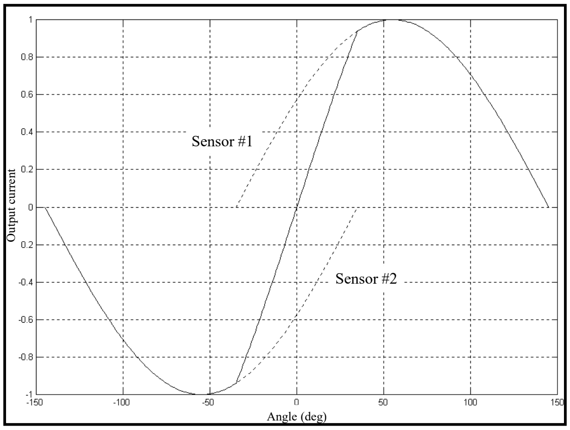
Analogic Sun Sensors

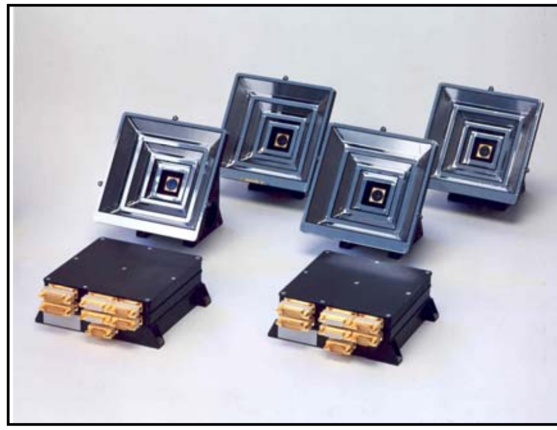




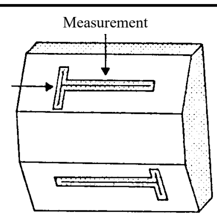
$$I(\vartheta) = I(0) d^{\mathrm{T}} n = I(0) \cos \vartheta$$





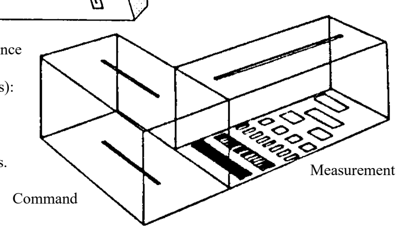


Digital Sun Sensors

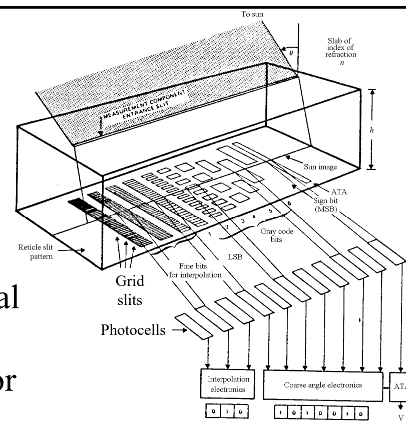


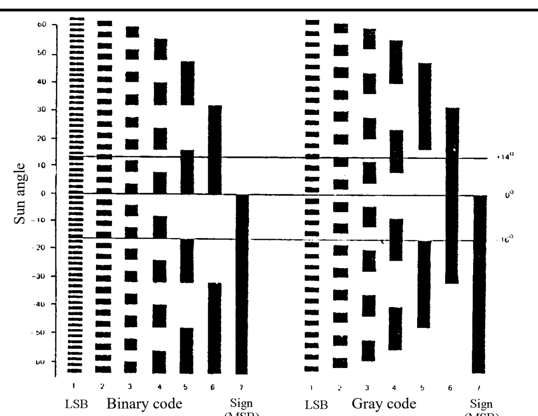
Command: sun presence

Measurement (4 parts):
1) ATA,
2) Sign bit,
3) Code bits,
4) Interpolating bits.



Digital Sun sensor



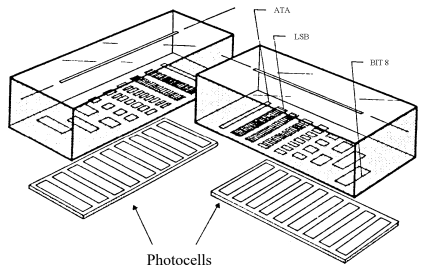


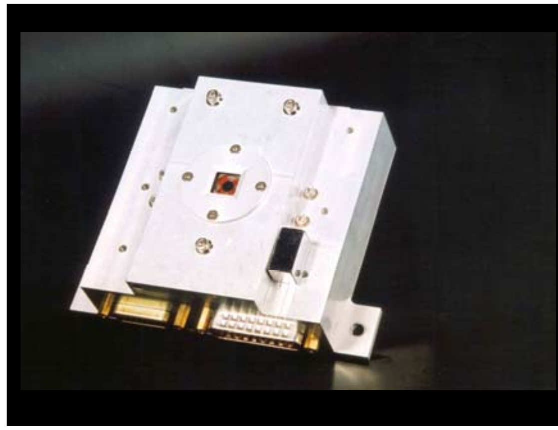
Binary and Gray code

The gain of the Gray code consists of the fact that the bit string, which represents the angle measure, changes one bit only at each digital step.

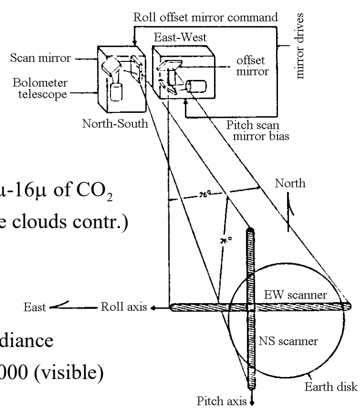
Decimal	Binary	Gray	Decimal	Binary	Gray
0	0	0	11	1011	1110
1	1	1	12	1100	1010
2	10	11	13	1101	1011
3	11	10	14	1110	1001
4	100	110	15	1111	1000
5	101	111	16	10000	11000
6	110	101	17	10001	11001
7	111	100	18	10010	11011
8	1000	1100	19	10011	11010
9	1001	1101	20	10100	11110
10	1010	1111	21	10101	11111

Double Digital Sun Sensor





Earth horizon sensor



Best range: 14μ-16μ of CO_2
(less high altitude clouds contr.)

Relative radiance
400 (IR) and 30,000 (visible)

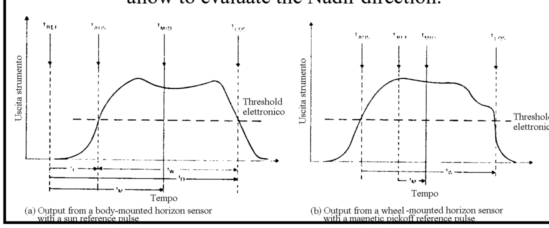
Earth horizon sensor

Measure two crossing times t_1 and t_2

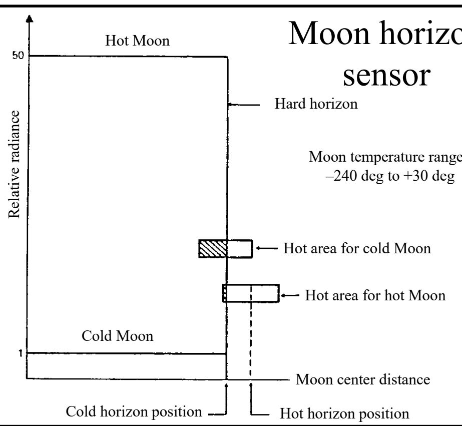
With angular speed ω, the measured angle is $\varphi = \omega(t_2 - t_1)$

Two measured angles, φ_1 and φ_2

allow to evaluate the Nadir direction.

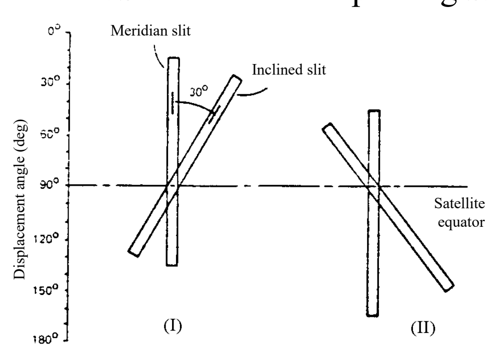


Moon horizon sensor

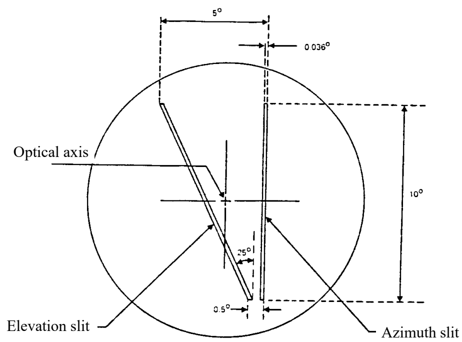


Moon temperature range:
–240 deg to +30 deg

Earth/Sun sensors for spinning S/C

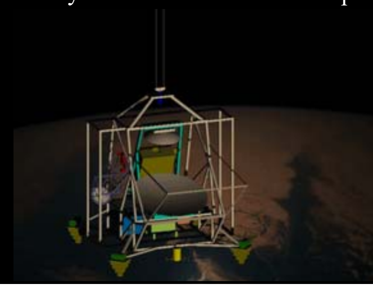


Star sensor for spinning S/C



The Archeops Star Sensor

- Archeops was a telescope on a spinning balloon payload, designed to map a significant fraction of the CMB sky with a microwave telescope.



REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 74, NUMBER 9

A fast star sensor for balloon payloads

Federico Nati,[a)] Paolo de Bernardis, Armando Iacoangeli, and Silvia Masi
Gruppo di Cosmologia Sperimentale, Dipartimento di Fisica, Università di Roma La Sapienza, P. A. Moro 2, 00185 Roma, Italy
Alain Benoit[b)]
Centre de Recherche sur les Très Basses Températures, BP166, 38042 Grenoble, Cedex 9, France
Dominique Yvon[c)]
SPP/DAPNIA/DSM, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France

(Received 13 January 2003; accepted 30 June 2003)

We developed a system to reconstruct the attitude of balloon borne spinning experiments, where high accuracy (about 1′) and high rotation speed (up to tens of degrees per second) are required. It is based on a stellar sensor, and gathers together hardware simplicity, cheap components, high resolution, and sensitivity. It is composed of an optical mirror (diameter 40 cm), an array of 46 fast and sensitive photodiodes, and low noise readout electronics. It was designed for the Archeops experiment, a balloon borne millimetric telescope whose goal is to generate high resolution maps of large regions of the sky, to study the temperature anisotropies of the cosmic background radiation.
 [DOI: 10.1063/1.1602961]

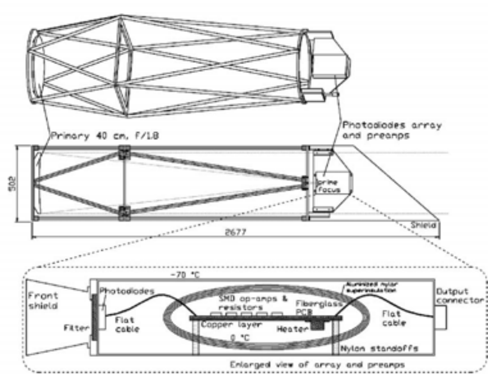


FIG. 1. Telescope frame for the star sensor location of the various components and internal details of the photodiodes box.

Archeops star sensor

igura 3.1: *Fotografia del sensore visto da davanti al telescopio. In primo piano si vede la scatola dei fotodiodi e dello stadio di preamplificazione posta direttamente davanti allo specchio, con i riscaldatori nel fuoco. Si nota anche il sistema per fuocheggiare l'apparato. La foto è stata scattata subito prima del volo di Trapani.*

Figura 3.17: *Foto della scatola dei sensori con l'elettronica di preamplificazione utilizzata nel volo di Trapani.*

Archeops star sensor

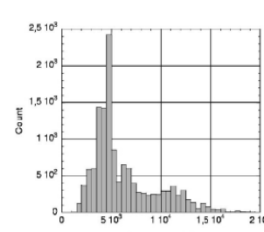
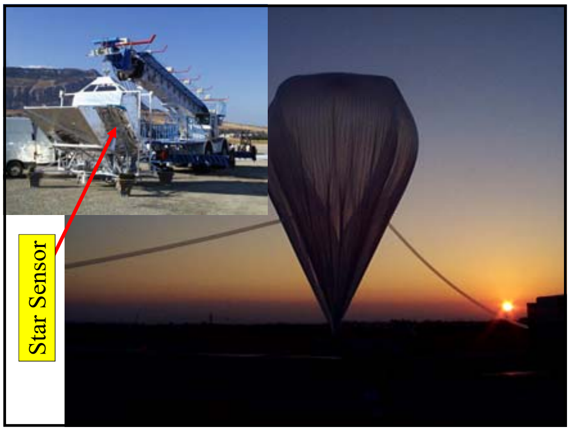
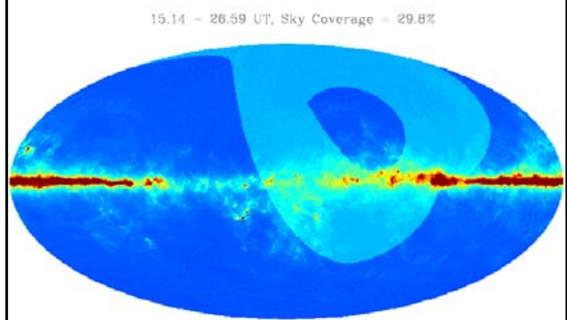


Figura 3.24: *Fotografia della finestra dei sensori (è visibile l'array di 46 fotodiodi) con il filtro Schott OG530 montato. Questo è il filtro scelto per il volo di Kiruna per ottimizzare il numero di stelle visibili nelle ore diurne.*

FIG. 2. Star temperature distribution of the Hipparcos/Tycho catalog. The Red giant peak is clearly seen, providing the hope that most detected stars are redder than the sky.

Da Nati et al. Mem. S.A.It. 2008





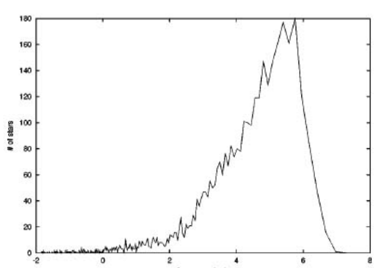


FIG. 6. Histogram of amplitudes of star candidates detected in the Kiruna flight (night).

4174 Rev. Sci. Instrum., Vol. 74, No. 9, September 2003

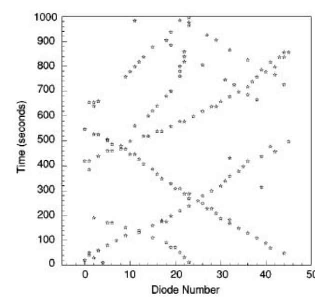
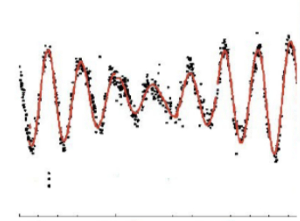


FIG. 7. This graph shows the diode number vs time of large amplitude candidate stars as seen by the stellar sensor telescope and the star detector software. Bright stars trigger the star detector every turn (20 s). They are seen as "tracks" in this plot: as the sky moves in front of the balloon, the star triggers move from one photodiode to the next.

Archeops star sensor

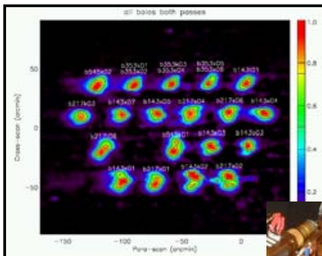
The pointing solution was reconstructed with about 1' RMS, by means also of other sensors, like gyros



Da Nati et al. Mem. S.A.It. 2008

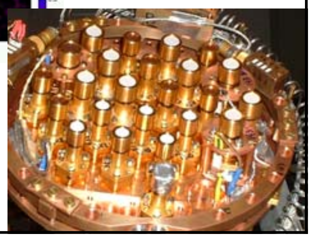
Optical Gyroscopes

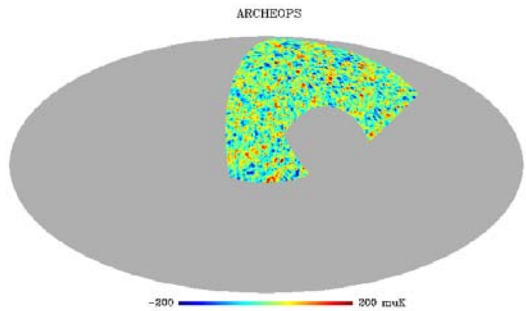
- They are based on the Sagnac effect (see http://www-3.unipv.it/donati/papers/2c.pd, Shamir, Adi, An overview of Optical Gyroscopes Theory, Practical Aspects, Applications and Future Trends, May 16, 2006
- Terry Pearson, How a gyroscope works, Febuary 1997, www.gyros.freeserve.co.uk) in which two light waves traveling in opposite direction in the same closed loop and generated by the same source, undergo a phase shift proportional to the rotating speed of the closed loop with respect to the inertial frame.Both laser and fiber optic gyros replaced mechanical gyros



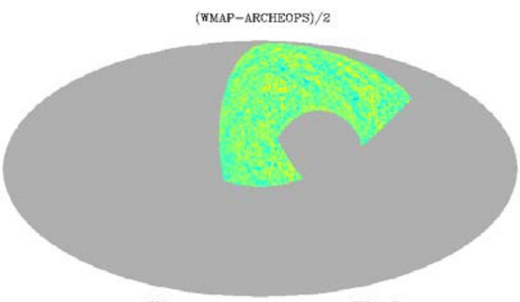
Jupiter scans

Focal Plane

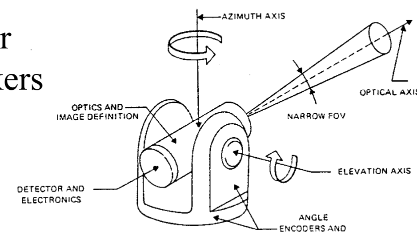


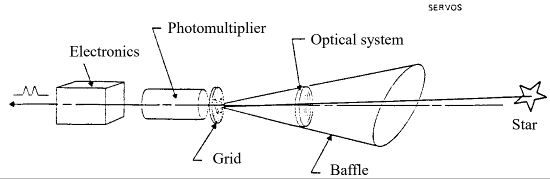


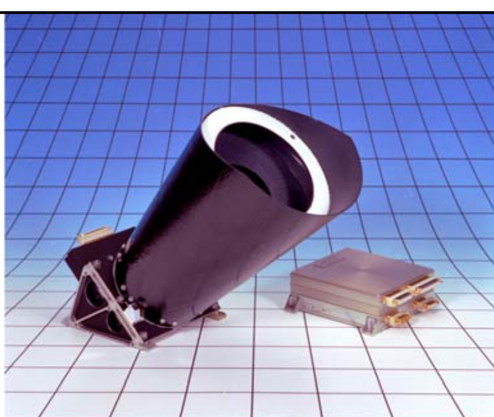
Archeops – Kiruna 2002



Star Trackers







OLIMPO star camera

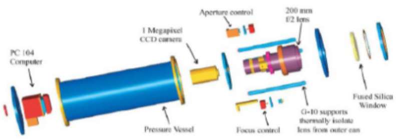
The camera is a Qimaging Retiga Exi CCD and the PC is a 266 Mhz Linux box. The system is provided by the CNR of Firenze (A. Boscaleri).

A PC-104 computer is mounted inside the star camera pressure vessel. The computer runs the software that processes the CCD images.
The computer can also command the stepper motors for autofocus, and regulates the lens temperature.

The system sends the right ascension and declination of the center of the image to the flight computer, which will communicate with the TM and the data storage system.

Da Nati et al. Mem. S.A.It. 2008

BLAST star camera



Mechanical drawing of star camera assembly. The design is based on an integrating CCD camera coupled to 200 mm f/2 lens with a 2° × 2.5° field of view. The entire system in contained in a pressure vessel.

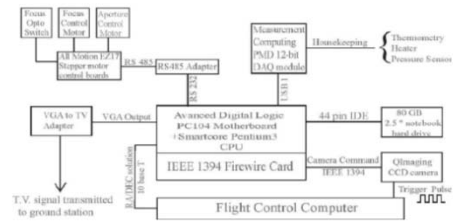
Using a system similar to the BLAST one, OLIMPO camera should be capable of providing a reconstructed pointing solution with an absolute accuracy < 5″. The system is sensitive to stars down to magnitudes ~ 9 in daytime float conditions.

It combines a 1 megapixel CCD with a 200 mm f/2 lens to image a 2º × 2.5º field of the sky. An internal computer controls the temperature, can adjusts the focus, and determines a real-time pointing solution at 1 Hz.

See M. Rex, E. Chapin et al., arXiv:astro-ph/0605039v1

Da Nati et al. Mem.S.A.It. 2008

ACS, sensors, data logging...



M. Rex, E. Chapin et al., arXiv:astro-ph/0605039v1

CCD specifications

	ISC	OSC
QImaging Camera	PMI 1401	Retiga EXi
CCD Sensor	Kodak KAF-1401	Sony ICX285
Light Sensitive Pixels	1312 × 1024	1360 × 1036
Pixel Size	6.8 μm × 6.8 μm	6.45 μm × 6.45 μm
Digital Output	14 bit	12 bit
Pixel Well Depth	45,000 e⁻	18,000 e⁻
Read Noise	20 e⁻	8 e⁻

Different choises can be made for CCD cameras, depending mostly on flight conditions (day or night) and scan strategy, which puts an upper limit to the integration time. Deeper well depths allow longer integration times (typically up to 200-300 ms), necessary with daylight. While having more bits per e- means more sensitivity during the night, when lower integration time is allowed (about 20-30 ms).

Scanning speed limits the integration time because, if too high, will result into a smearing of the star blobs through the pixels.

Da Nati et al. Mem. S.A.It. 2008

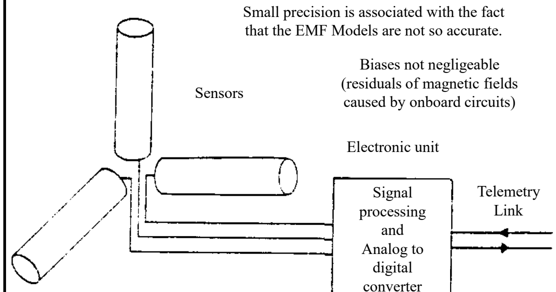
Magnetometers

$$V = \int E\, dl = \frac{d\Phi_B}{dt}$$

They may be used at altitudes less than 1,000 Km, only.
(Earth magnetic field decreases with radius as $1/r^3$)

Small precision is associated with the fact that the EMF Models are not so accurate.

Biases not negligeable (residuals of magnetic fields caused by onboard circuits)



Typical GN&C Sensors (Wertz)

Sensor	Typical Performance Range	Wt Range (kg)	Power (W)	Some Typical Suppliers
Inertial measurment unit (gyros & accelerometers)	Gyro drift rate = 0.003°/hr to 1°/hr accel. linearity = 1 to 5 x 10^{-6} g/g² over range of 20 to 60 g	3 to 25	10 to 200	Northrop, Bendix Kearfott, Honeywell, Hamilton Standard, Litton, Teledyne
Sun sensors	Accuracy = 0.005° to 3°	0.5 to 2	0 to 3	Adcole, TRW, Ball Bros
Star sensors (scanners & mappers)	Attitude accuracy = 1 arc sec to 1 arc min	3 to 7	5 to 20	Ball Bros, Honeywell, Hughes
Horizon sensors • S canner • F ixed head (static)	Attitude accuracy = 0.1° to 1° = 0.1°	2 to 5 2.5 to 3.5	5 to 10 0.3 to 5	Barnes, Ithaco, Lockheed Barnes, Lockheed, Quantic
Magnetometer	Attitude accuracy = 0.5 to 3° (may need second reference)	0.6 to 1.2	< 1	Schonstedt, Develco

Attitude Determination Systems

	CES & Magne-tometer	CES & Sun Sensor & ARU	CES & ARU (Gyro-compas.)	Star Tracker Plus ARU			GPS & ARU (IFOG)
				Mechanical	Laser	IFOG	
Performance Deg. (3 sigma)	Absolute pitch & roll: 0.09 yaw: 0.5 Relative p&r < .05	Absolute pitch & roll: 0.09 yaw: 0.03 Relative p&r < .05	Absolute pitch & roll: 0.09 yaw: 0.05 Relative p&r < .05	< 0.01 all axes	< 0.01 all axes	< 0.01 all axes	< 0.01 all axes
Flight Proven	Yes	Yes (mech gyro) No (RLG or (IFOG)	Yes (mech gyro) No (RLG or (IFOG)	Yes	No	No	No
Dev. Status	---	---	---	---	Space qual needed	Dev. & space qual needed	Ground test experiment & dev., & space qual needed
Est. reliability	current 3-7 yrs.	current 3-7 yrs.	current 3-7 yrs.	worst 2-5 yrs.	third best	second best	best
Est. recurring cost	$300K-$400K	$400K-$500K plus ARU	$300K-$400K plus ARU	$1.6M-$2.7M	$1.35M-$2.2M	$900K-$1800K plus	$250K - $400K plus
Est. non-recurring cost	zero	ARU if needed	ARU if needed	zero	Minimal Since ongoing (MSX)	$3-5 mil	$3-7 mil for GPS, $3 mil for ARU