NORTHROP GRUMMAN

DEFINING THE FUTURE

Nanosat Navigation

April 28, 2006

Hobson Lane
Section Head, Payload Pointing and Control
Northrop Grumman Corporation

Agenda

- **Introduction to GNC**
  - Terminology
  - ACS/GNC System Architectures
  - Focus on navigation (sensing)
- **Attitude Determination**
  - SIAD + Gyros
  - Earth Tracker + Sun Sensor + Gyros
- **Ephemeris Determination**
  - Onboard
    - GPS
    - Transponder
  - Ground Tracking
    - Optical
    - Laser
    - Radar
    - Com Link
- **Integrated 6-DOF Navigation**
  - MANS
  - X-Nav

Industry Terminology

- **Attitude Determination and Control Subsystem (ADCS or ACS)**
  - Active stabilization or feedback control of satellite attitude relative to inertial space or planetary body
- **Guidance Navigation and Control (GNC)**
  - Typically used in the missile and submarine world, where autonomous systems must control to a position trajectory in addition to attitude
    - Usually 6-DOF
    - Sometimes 6-DOF sensing and 4-DOF actuation
      - Turn and burn, R/P/Y+V for airplanes, nonholonomic dynamics equations
- **Reaction Control System (RCS)**
  - Maintains prescribed attitude during thrusting or maneuvering
  - Often associated with GNC or NASA shuttle missions
- **Orbital Operations (OO)**
  - Ground commanding of ACS and ΔV to accomplish desired ground coverage and phasing
  - Ground tracking of satellite ephemeris

NORTHROP GRUMMAN

Satellite GNC Options

- **Sensors**
  - Inertial Measurement Unit (IMU) – mechanical or optical gyros and/or accelerometers
  - Star Tracker Assembly (STA) – (q-out vs. camera)
  - Coarse and Fine Sun Sensors (CSS, FSS)
  - Three-Axis Magnetometer (TAM)
  - Earth Horizon Sensors
  - GPS or ground tracking (laser, RF, optical) for ephemeris
- **Actuators**
  - Reaction Wheel Assemblies (RWA) or Control Moment Gyros (CMG)
  - Magnetic Torquers (MTA)
  - Propulsion—Chemical, Electrical (Ion, Hall Effect, Plasma), or Digital
  - Movable masses or gravity gradient boom
  - Solar or aerodynamic vanes
- **Architectures**
  - Spin stabilized
  - Dual spin stabilized
  - 3-axis stabilized (zero momentum)
  - Gravity Gradient
  - 4-DOF ("Turn and Burn") vs. 5 or 6-DOF
- **Attitude: sun, inertial, nadir, relative to other satellites**
- **Orbit: LEO, MEO, HEO, GTO, GEO, L1/L2, Interplanetary, Deep Space**

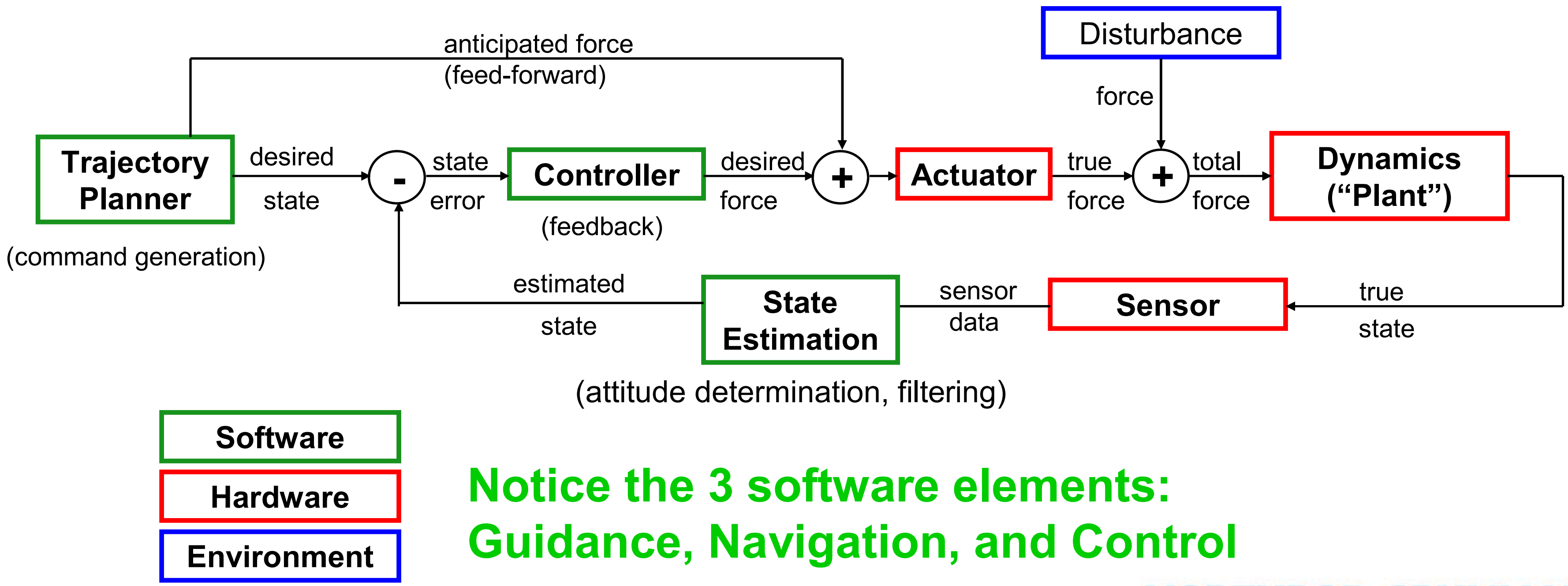
ACS System Examples

- **Spin Stabilized (Hughes Patent)**
  - Accurate pointing without RWA (nutation damper maintains passive stability about spin axis)
  - Improved SRP symmetry, but reduced solar power and communications efficiency
  - Example: Syncom
- **Dual Spin**
  - Spin stabilized body with despun payload/antennae platform
  - Improved communications efficiency, but increased mechanism complexity
  - Example: Tacsat
- **Gravity Gradient**
  - Differential in gravitation and centripetal acceleration pulls “long” axis down
  - Robust, no expendables, simple/cheap, passively stable, low accuracy (1 deg typical), 2-DOF
  - Example: JIMO, GOES II
- **Magnetic or Aero/Solar Control**
  - Low accuracy, simple, low ACS mass. Passive or active.
- **3-Axis Stabilized**
  - Increased hardware (RWAs or CMGs) and ACS complexity, but greater flexibility and pointing accuracy
  - Maximum solar power and communications efficiency
  - Examples: most modern satellites

NORTHROP GRUMMAN

Feedback Control Basics

- **Trajectory planners ("command generators", or feed-forward) are often neglected because feedback is so robust**
  - Trajectory planners can dramatically reduce controller actuation, improve controller accuracy, and reduce unwanted dynamics excitation
- **State estimation can add precision, but isn't required eliminated for many systems**



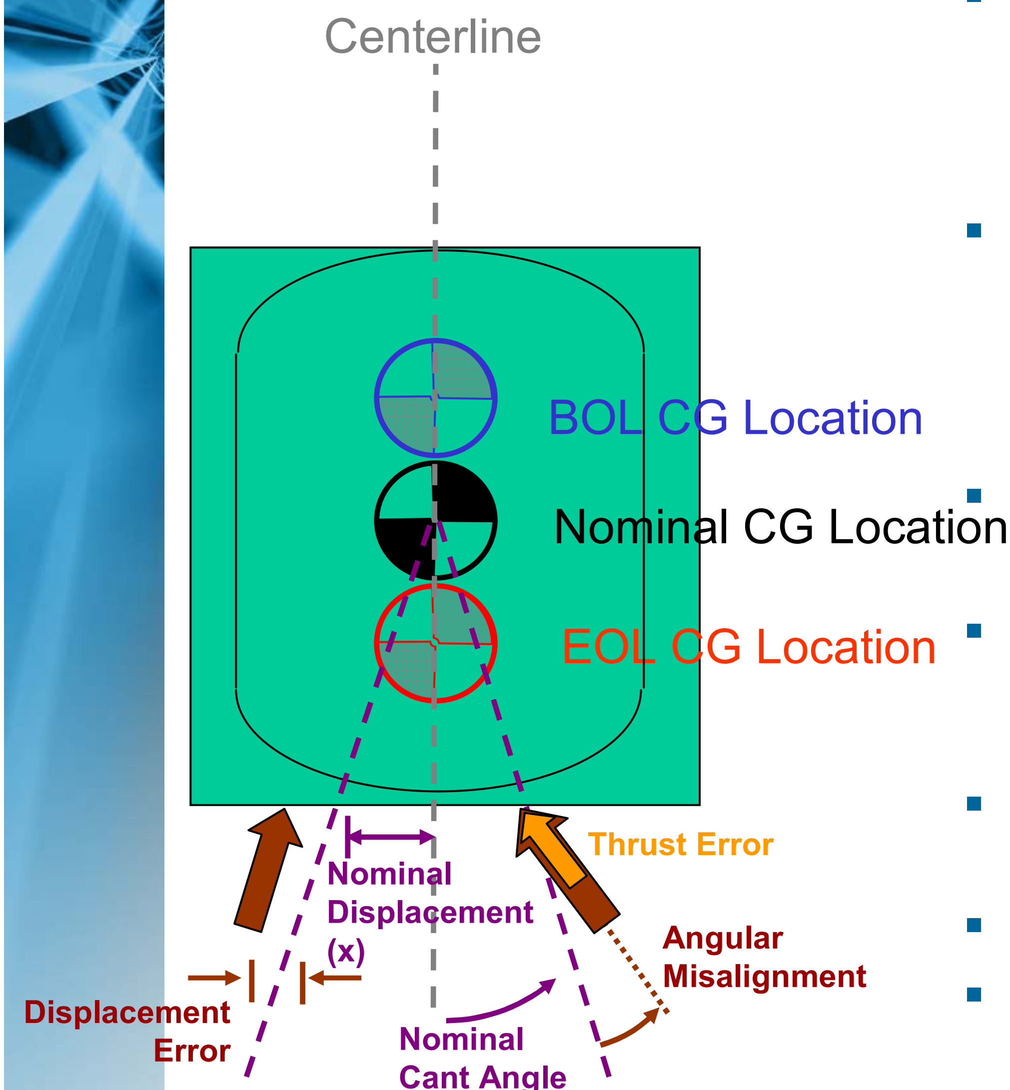
Notice the 3 software elements: Guidance, Navigation, and Control

Some Example GNC Challenges

- **Sensor/actuator alignment and coordinate transformations**
- **Attitude estimation**
  - Sun or Earth gives 2-DOF each--must be combined to get 3-DOF solution
  - "Lost in Space" problem for STA star catalog searching
  - Maximum STA rate due to blur and CCD sensitivity
  - IMU gives high bandwidth inertial solution, but bias & drift must be compensated with inertial sensors
  - KF adds persistence ("time averaging") and sensor fusion/blending utilizing dynamics model to provide large improvement in accuracy without sacrificing bandwidth
- **Actuated appendage dynamics**
  - Reaction moments (motor + rotor momentum) significant for complex S/C
- **Solar array, antennae, payload elastic dynamics**
- **Round-off error (truncation)**
- **Rigid body gyroscopic effects**
- **Instability during mode transitions or unplanned events**
- **Fault management response (the IR in FDIR)**

NORTHROP GRUMMAN

Thruster Misalignment and CG Migration



- **As fuel is expended CG migrates downward**
  - CG location calculated after each major mission phase (burn)
- **Pitch/Yaw Torque Components**
  - Angular misalignment
  - Lateral misalignment
  - Thrust mismatch
- **Roll Torque Components**
  - Angular misalignment
- **ΔV thruster configurations can employ multiple "main engines" or a single thruster**
- **Reaction torque counteracted by the ACS or RCS system**
- **Bladdered tanks push CG to one side**
- **"Blowdown" tanks waste fuel and have sloshing**

Navigation is Paramount

- **Navigation accuracy determines control accuracy**
  - ACS seldom limited by actuator accuracy
    - Creative control techniques can usually overcome most actuator quantization and repeatability techniques
    - If you can't sense your attitude accurately, no innovative control law can ever produce a system with accurate control
  - Optimal estimators (Kalman Filters) can improve upon raw sensor accuracy
    - Utilize knowledge of dynamics to "average" measurements over time despite the changing vehicle state (attitude + position)

NORTHROP GRUMMAN

Navigation Onboard or by Ground

- **Attitude navigation usually happens onboard for commercial and science satellites**
  - Satellite must be able to point communications antennae to accomplish high bandwidth link to ground
    - Not usually an issue for nanosats using omnidirectional antennae
  - Satellite can maintain high bandwidth control without taxing communication link to relay sensor data
  - Ground tracking of satellite attitude without onboard sensors is usually impossible or extremely inaccurate
- **Ephemeris (positioning) navigation generally utilizes ground stations**
  - Various ground-based sensors used
    - Communications link—bearing and/or velocity (Doppler)
    - Optical tracking—bearing only
    - Laser tracking—range and/or bearing
    - Radar—range and/or bearing
  - Recent advances in GPS radiation hardening have begun to make onboard ephemeris navigation possible
    - Other autonomous onboard systems have been proven (MANS)

NORTHROP GRUMMAN

Sun Sensors

- **Coarse sun sensors (CSS)**
  - Can be as simple as a single photodiode beneath a slit
  - Typically have a FOV of >150° in 2 axes and <0.1° precision
  - No power required, low mass

- **Digital sun sensors or fine sun sensors (FSS)**
  - Employ a vernier slit pattern or linear photodiode array for more precise sun angle measurement
  - Typically have a FOV of >150° in 2 axes and <0.02° precision
  - Little or no power required, low mass

- **For nanosats, can you use the differential power between several fixed solar panels to estimate the sun line?**

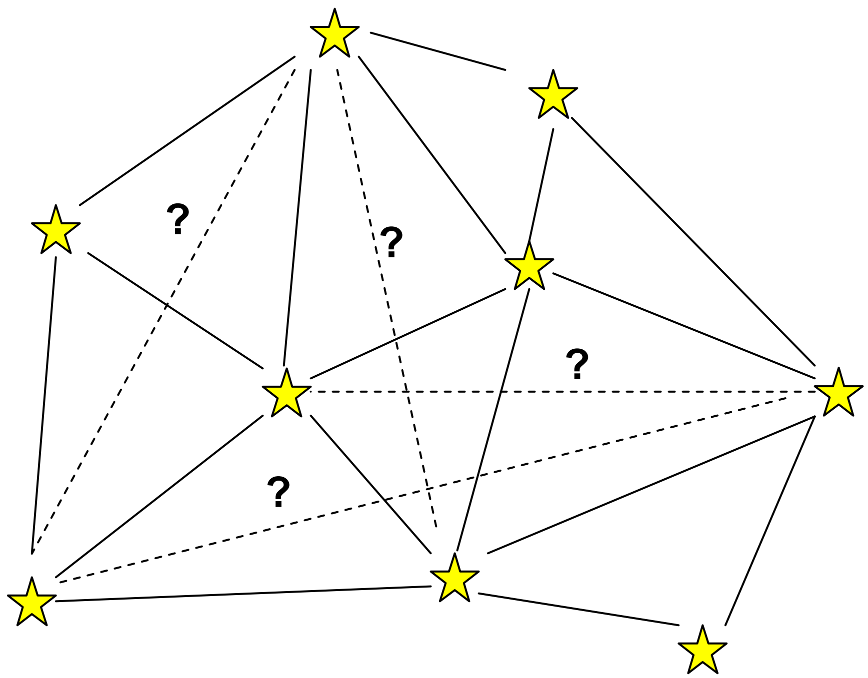
Star Trackers

- **The heart of a stellar inertial attitude determination system (SIAD) is the accuracy of the inertial update from the star tracker**
  - No matter how precise the gyros, accuracy of bias updates from STA determines ultimate pointing accuracy
- **STAs generally have 2 modes**
  - “Lost In Space”
    - Star catalog searching is analogous to least squares fitting or Google’s index searching
    - Star pairs, triad, or quad geometries are sometimes used as sort keys
  - Attitude tracking
    - Incremental motion of star field tracked
- **Some STAs push the envelope for high rate performance by incorporating additional modes**
  - Rate limit driven by integration period and update rate of camera
    - Update rate limited by CCD sensitivity
  - Smearing and streaking of star images due to vehicle tumbling
- **Some produce an attitude quaternion (“q-out”) others merely output the x-y positions of stars**

NORTHROP GRUMMAN

Star Catalog Searching

- **Just like Google, indexing & sorting is the key**
  - Reduces processing bandwidth by being smart about search
  - Reduces search time



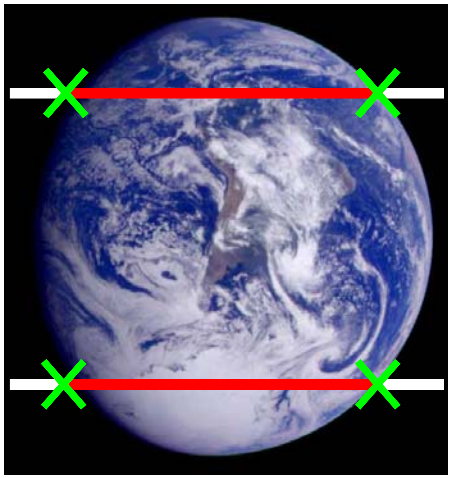
Unsorted Star Pair Index

Star ID 1	Star ID 2	Separation Distance	Summed Brightness
1	2	0.25°	3.5 M
1	3	0.32°	2.1 M
1	4	0.58°	3.4 M
⋮	⋮	⋮	⋮
2	3	0.13°	1.6 M
⋮	⋮	⋮	⋮

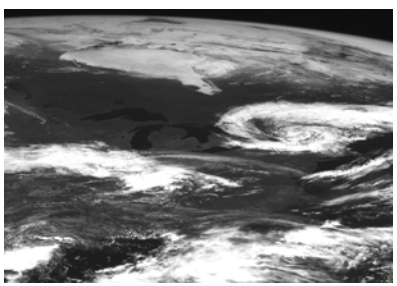
- **How many pairs are enough? N^2 ?**
- **How should it be sorted?**
- **How many connections should be considered? 2 (segment)? 3 (triangle)?**

NORTHROP GRUMMAN

Scanning Earth Horizon Sensors



- Earth Sensors scan the Earth using mirrors to direct infrared (IR) light from the Earth to a bolometer (IR detector diodes)
- Earth limb located at 4 points (the ends of the chord scans)
- Closed form solutions for a circle’s center possible from the chord lengths and 4 end coordinates.
- Also provides approximate altitude estimate (too inaccurate for ephemeris determination)



- IR radiation reflected/emitted from clouds at limb of Earth causes an attitude estimate error of as much as 0.15°

- Typically used for Geosynchronous (GEO) satellites pointed at the Earth with moderate accuracy.
  - For low Earth orbit (LEO) satellites, scan angle required usually becomes prohibitive (massive, expensive)

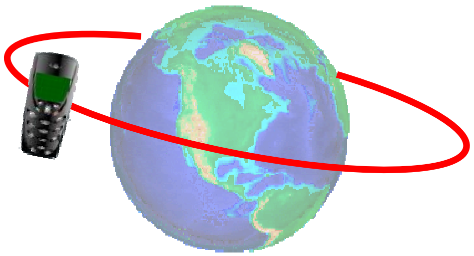
Ephemeris Determination

- **Ephemeris Determination**
  - Onboard
    - GPS – only recently became ubiquitous for satellite navigation
    - Earth Transponders/Beacons – not generally employed
    - MANS – Microcosm Autonomous Navigation System
    - X-Nav – Naval stellar navigation applied to satellites using pulsars
  - Ground Tracking
    - Radio Frequency (RF)
      - Deep Space Network (DSN) – 3-DOF using multiple ground stations to triangulate
      - Communications link can provide range and/or range rate (Doppler) estimation (1-DOF or 2-DOF for a single ground station)
        - Bearing measurements are generally very inaccurate
    - Optical
      - Amateurs regularly track the bearing to satellites with off the shelf telescopes (2-DOF bearing measurements for a single ground station)
    - Laser
      - Provide range and accurate bearing for full 3-DOF solution
    - Radar
      - Provide range and relatively accurate bearing for full 3-DOF solution

NORTHROP GRUMMAN

GPS

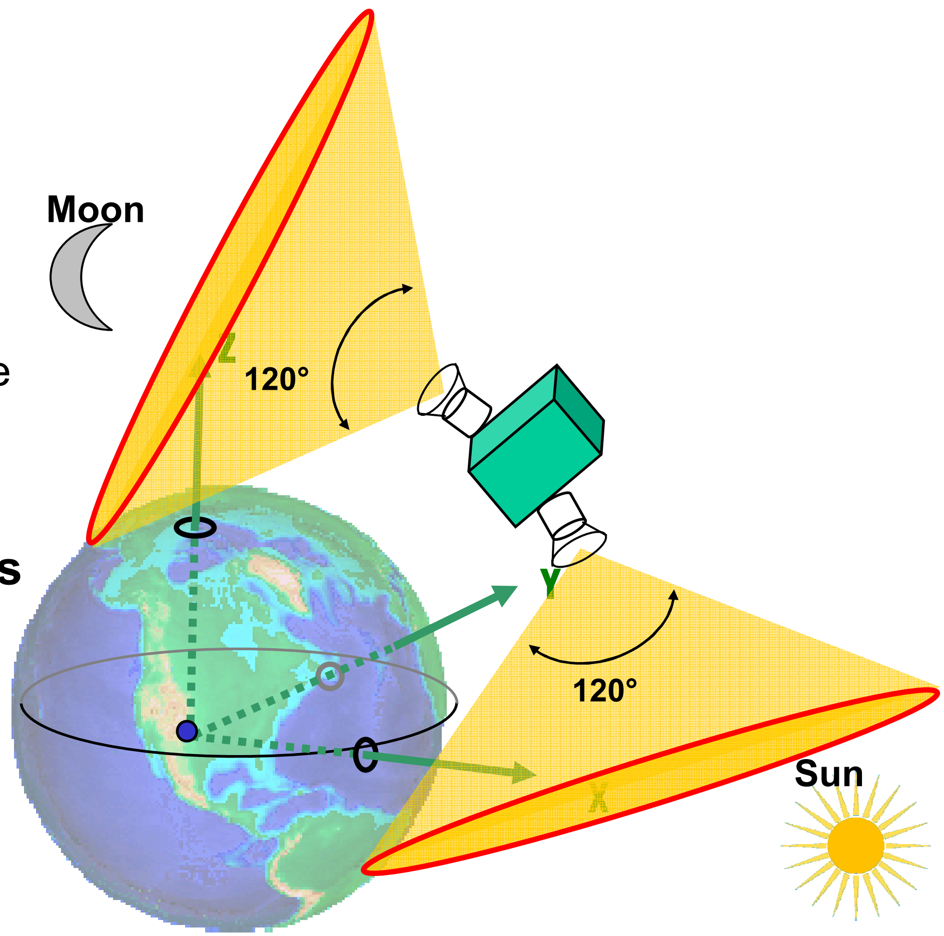
- **Modern satellites often include massive GPS receivers (GPSRs) and antennas for onboard navigation in LEO**
- **GPS signals are not designed for use above LEO altitudes**
  - Kalman filtering techniques and optimized antennas make GPS at GEO possible
- **If only cell phones could fly!**
  - Modern cellphone capabilities would make excellent CubeSats if they could survive the environment
    - Radio transceiver – ground communication link?
    - GPS receiver – ephemeris navigation?
    - Camera – star camera?



NORTHROP GRUMMAN

MANS

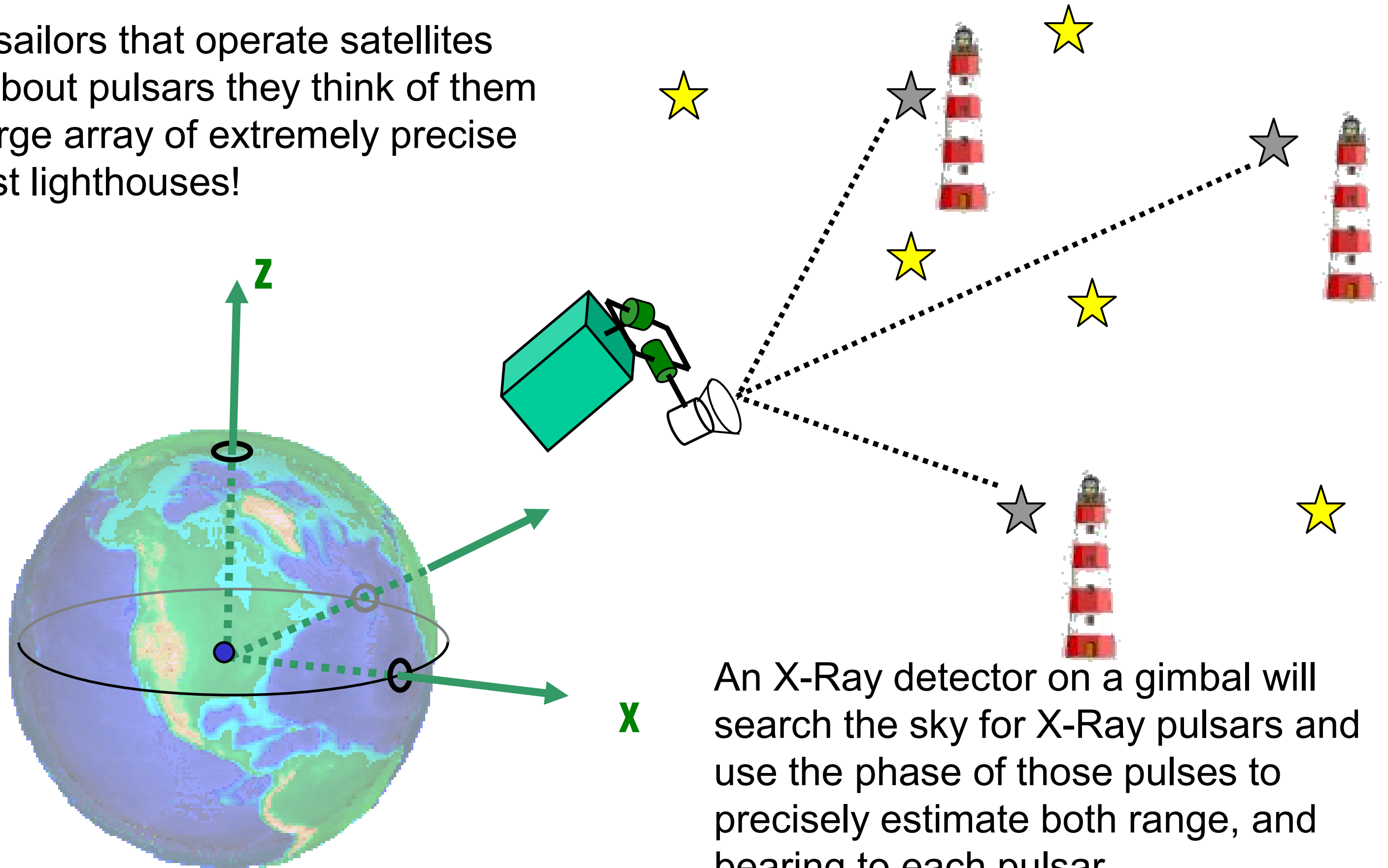
- **Two Scanning IR Earth Sensors**
  - Simultaneously scan for the most obvious celestial references:
    - Earth horizon
    - Sun centroid
    - Moon disc edges
  - Triangulation provides both attitude and ephemeris
  - Closed form solution and Kalman Filtered solution
- **MANS = Microcosm Autonomous Navigation System**
- **First demonstrated on STEP0 in early 90's**
  - Determined ephemeris to 150 m precision
  - Determined attitude to < 0.01 deg.
  - Sponsored by Air Force Phillips Laboratory



NORTHROP GRUMMAN

X-Ray Navigation

When sailors that operate satellites learn about pulsars they think of them as a large array of extremely precise and fast lighthouses!



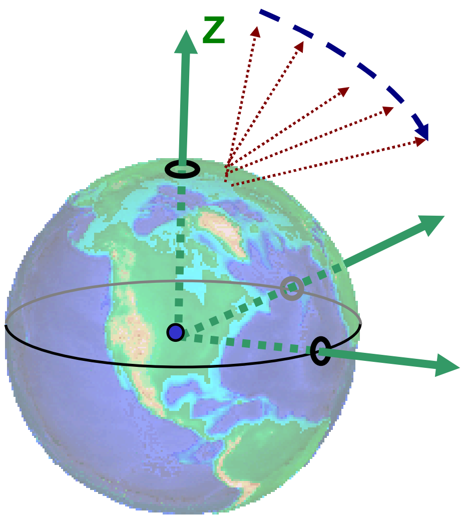
An X-Ray detector on a gimbal will search the sky for X-Ray pulsars and use the phase of those pulses to precisely estimate both range, and bearing to each pulsar.

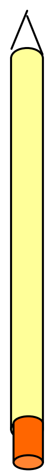
This technique may allow full 7-DOF (position + attitude + time) navigation without any dependence on man-made sources

Sponsored by the Naval Research Laboratory (NRL)

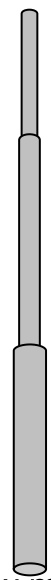
Ground Tracking

- **Multiple measurements from a single ground station can be used to determine ephemeris if they are correlated over time**
  - Can be batch processed (post-processed)
  - Can be Kalman filtered in real time
  - Error statistics can be gleaned from overlapping batches





For range and bearing measurement imagine a pencil with the eraser fixed firmly at the ground station (with a glob of clay?) and the satellite allowed to rotate/pivot at the tip.



For bearing measurements imagine a loose and well-greased telescoping car antennae with the base fixed firmly at the ground station.

For range measurements imagine a string pulled taught between the ground station and the satellite.

Using these analogies, can you get a feeling for how many measurements it would take to "fix" a satellite in space? Can you get a feel for geometric dilution of precision (GDOP)?

NORTHROP GRUMMAN

Passive or Semi-Passive Stabilization

- Spin stabilization
- Dual-Spin stabilization
- Gravity gradient
- Aerodynamic (badminton "shuttle cock" effect)
- Gyrocompassing
- Magnetic

- Can you think of ways that passive stabilization techniques can be combined with active elements to accomplish 3-axis stabilization?

NORTHROP GRUMMAN

References

Bowers, J. L., and Rodden, J. J., "Orbital Gyrocompassing Heading Reference," AIAA Paper No. 67-587, Aug 1967.

Chobotov, Vladimir A., Orbital Mechanics, 2nd Edition, 1996.

Chobotov, Vladimir A., Spacecraft Attitude Dynamics and Control.

Dutton, Ken, The Art of Control Engineering, 1997.

Franklin, Gene F. & Powell, David J., Feedback Control of Dynamic Systems, 3rd Edition, 1994.

Ginsberg, Jerry H., Advanced Engineering Dynamics, 2nd Edition.

Kronman, J. D., "Experience Using GPS For Orbit Determination of a Geosynchronous Satellite," *Proceedings of the Institute of Navigation GPS 2000 Conference*, September 2000.

Laverty, N. P., McAloon, K.J., Roberts, J. L., Williams, I. J., "Multi-Mission Attitude Determination and Autonomous Navigation (MADAN)," TRW Defense and Space Systems Group, Space Park, AAS 80-029.

Quartararo, Richard, Spacecraft Attitude Determination and Control, UCLA Extension, 1998.

Sciavicco, Lorenzo & Siciliano, Bruno, Modeling and Control of Robot Manipulators, 1996.

Sheikh, Suneel I. and Pines, Darryll J. "Spacecraft Navigation Using X-Ray Pulsars," University of Maryland and U.S. Naval Research Laboratory, *Journal Of Guidance, Control, And Dynamics*, Vol. 29, No. 1, Jan–Feb 2006.

Vallado, David A., Fundamentals of Astrodynamics and Applications, 2nd Edition, 2001.

Wertz, James R. "Autonomous Spacecraft Navigation System," US Patent 5,109,346, issued April 28, 1992.

Wertz, James R. and Hosken, Robert W., "Microcosm Autonomous Navigation System On-orbit Operation," AAS 95-074.

Wertz, James R., Spacecraft Attitude Determination and Control, D. Reidel Publishing Company, 1997.

Zarchan, Paul and Musoff, Howard, Fundamentals of Kalman Filtering, A Practical Approach, AIAA, 2000.

NORTHROP GRUMMAN