Navigation Overview

Strategic and Technical Aspects of Planetary Small Satellite Missions

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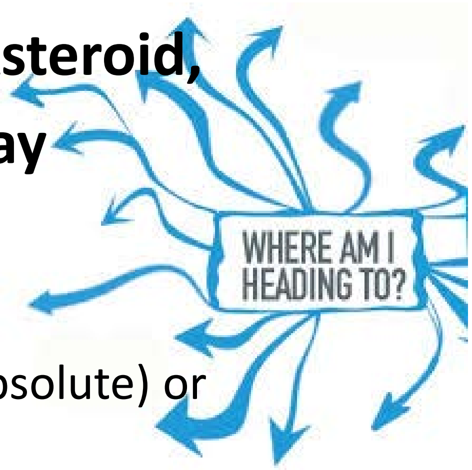
Agenda

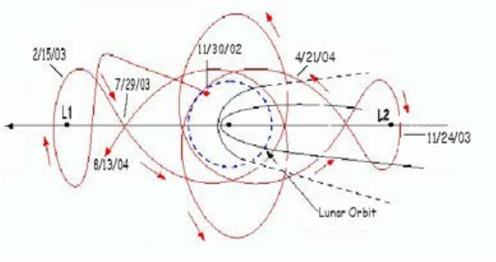
- Orbit Regimes
- Basic OD Concepts
- Data Systems and Types
- Influences on Measurements
- Planetary Navigation Options
- Future Directions

Defining Navigation Regimes

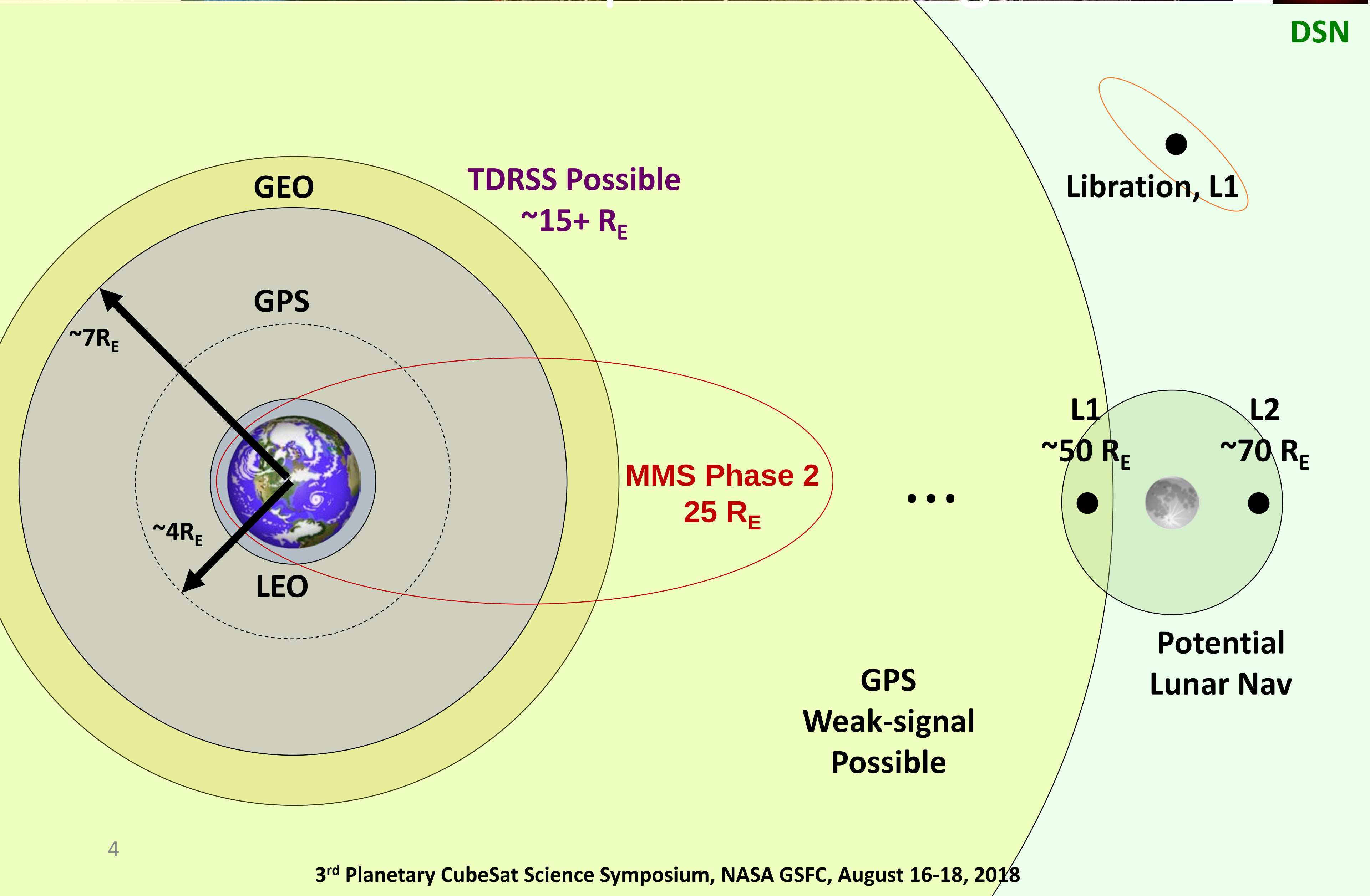
- **Near Earth – central body is Earth or within 2M km of earth**
- **Planetary – Moon, Planets and their moons, Asteroid,**
- **Heliocentric – Non-Planetary designs, Drift away**



- **Navigation refers to:**
  - Knowledge of the mission orbit wrt the central body (absolute) or wrt another object (relative)
  - Knowledge of where the object resided or currently resides in the orbit (definitive) or will reside in the future (predictive),
  - The trajectory design associated with achieving the mission,
  - How to modify the object's orbit to follow that trajectory,
  - And the time associated with each of these.



Notional summary
Near-Earth Operational Regimes



DSN

Libration, L1

TDRSS Possible
~15+ R_E

GEO

GPS

$\sim 7R_E$

$\sim 4R_E$

LEO

MMS Phase 2
25 R_E

• • •

L1
~50 R_E

L2
~70 R_E

Potential
Lunar Nav

GPS
Weak-signal
Possible

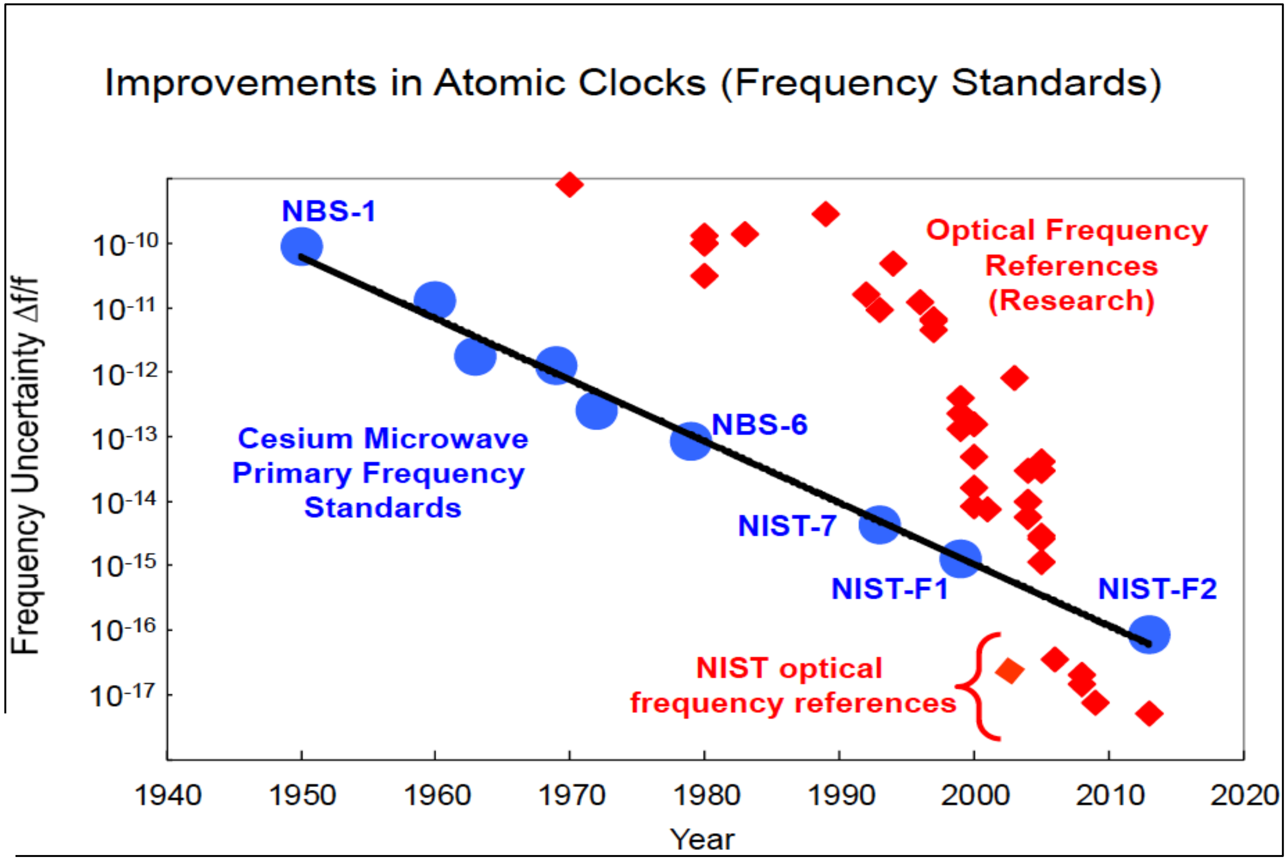
Forms of Direct Measurements

- Time Delay → Range (Distance)
- Differential Delay → Angle
- Frequency shift (Doppler) or Carrier Phase → Line of Sight Velocity
- Frequency Change Rate or Acceleration → Line of Sight
- One common element among each of these…

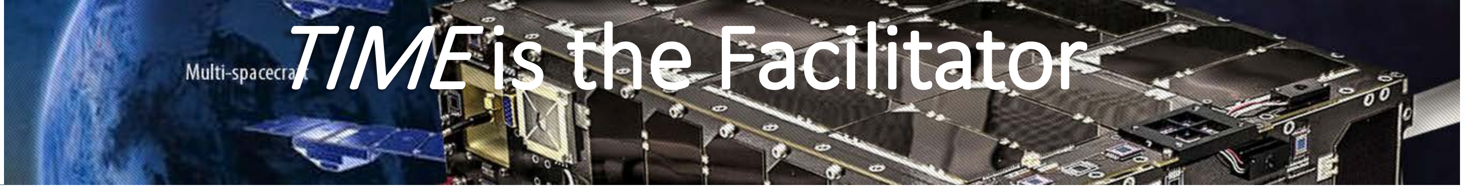
TIME

Time is Fundamental

Cs and USO



1 sec/100 days → **1 sec/316,881 years**



TIME is the Facilitator

- Ground element timing establishes boundary condition for end-user performance
- Applicable to communications, radiometrics, and science
- Sources clock and frequency
  - Delay accountability
  - Phase noise & jitter
  - Coherency

- Automatic exchange of timing state during a communication session enables:
  - TDMA type communication schemes - **Time-division multiple access** (**TDMA**) is a channel access method for shared-medium networks. It allows several users to share the same frequency channel by dividing the signal into different time slots
  - Autonomous or on-demand session establishment
  - Internet-like routing

Data Types & Systems

Measurement Type	Providing Systems
Range – tone, swept tone	GN, TDRS TTC, DSN
Range – PN	TDRSS, GPS, DSN (variation)
Doppler or Carrier Phase	All
Angles – Direct Observation	GN, TDRS (WSC SGL, SA & MA beams)
Celestial Navigation – Indirect Angles	Star Sensors, Earth/Sun Sensors
Delta Differenced One-Way Range - Angles	DSN with Quasars
Imaging/Optical Navigation	Cameras
XNAV	XNAV Pulsars

Range & Doppler can be either 1-way or 2-way
Both improved by differencing

Error Sources on Radiometrics

- Media – phase delay
- Oscillator stability – ground, relay, customer*
  - Local Oscillators and the respective Phase Lock Loop
  - Includes resolution of Numerically Controlled Oscillators (NCO)
- Thermal Noise
- Loop Order – ability to track higher order dynamics
- Signal to Noise Ratio & integration time
- Calibration
- Tone selection – resolution limitations
- Coherency – precision of turnaround
- Platform calibration – location, orientation

* - Does not apply to coherent operations; Can be differenced out with adequate source availability

Planetary Navigation

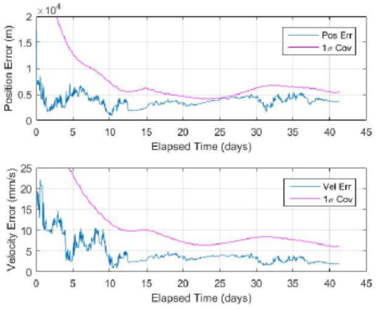
- Planetary Navigation options include traditional ground based and Onboard Celestial Navigation
- Traditional option includes the use of the NEN and DSN and a DSN compatible transponder, e.g. IRIS-V2 requiring multiple station contacts
- Onboard options include the use of Celestial Navigation, a self contained onboard system
  - Developed for libration and deep space missions
  - Equipment - quality depends on the mission and orbit regime & requirements
    - XPDR with ability to accept external reference and to output low phase noise Doppler (<<1mHz, like 0.3mHz)
    - Oscillator with Allan Variance <1e-12 (prefer 1e-13) over tau of 10-100 seconds
    - Accelerometer
    - Star sensor with wide FOV in E-W/Azimuth looking anti-sunward (can get earth-Moon, and other planets, with reference star in background
    - Onboard timing synchronous across all systems related to nav (XPDR, XLINK, C&DH, Nav processor, accelerometer, star sensor observables)
    - Processor
    - Xlink for Formation –incorporate relative Doppler and pseudo range, referenced to the same oscillator as the XPDR; the ambiguity has to be tunable or allow for the far field distances, but while maintaining near field accuracy.
- Improved accuracy (convergence) using onboard system, especially for frequent maneuvers for formation control and any momentum uploads
- Requirements, math specs, & Users' Guide that contain the specs for CelNav are available

Goddard Space Flight Center

Autonomous Celestial Navigation (CelNav)

- **Technology Demonstration Concept**:
  - Autonomous, on-board celestial navigation system fused with one-way radiometrics, accelerometers, Goddard Enhanced On-board Navigation System (GEONS), and Goddard Image Analysis and Navigation Tool (GIANT). Would provide autonomous Gateway navigation.

- **Relevance:**
  - Made up of existing high-TRL components with flight heritage (MMS, OSIRIS-Rex) and flight-proven software. Multi-center collaboration
  - Answers specific need for WFIRST flagship mission, common hardware proposed for Caesar and Lucy



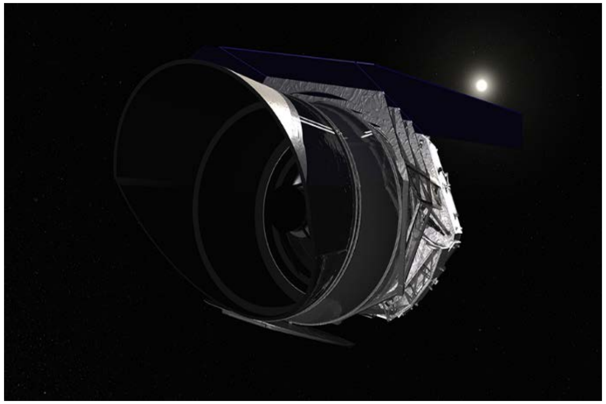
WFIRST CelNav*

On-board OD (CelNav + 1-way Doppler) for WFIRST
5 – 30 km, **15 - 50 mm/s**, 3-sigma RSS

Ground OD (NEN) based on recent experiences (multiple)
0.2 – 1 km, **200 – 500 mm/s**, 3-sigma RSS

Performance is orbit/mission dependent
Gateway-specific analysis pending

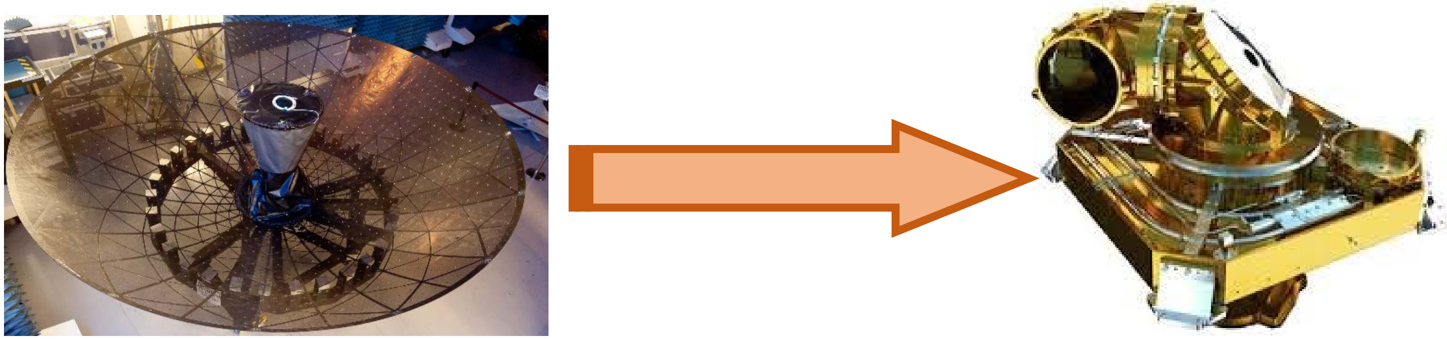
- **Relation to Current Activities:**
  - Testing of an autonomous celestial navigation system would directly support technology maturity for the WFIRST on-board navigation system.
    - Gateway & WFIRST on-board OD is more accurate for maneuver planning than ground based navigation alone and will save fuel, extending mission lifetime
    - Reduces DSN/NEN contact times for ranging
    - Aides relative navigation for potential WFIRST/Starshade mission



- **Gateway Requirements:**
  - Mass & power allocations, Gateway location(s) with Moon and Earth in the FOV, and access to ACS data will be required.

Incorporate Optimetrics

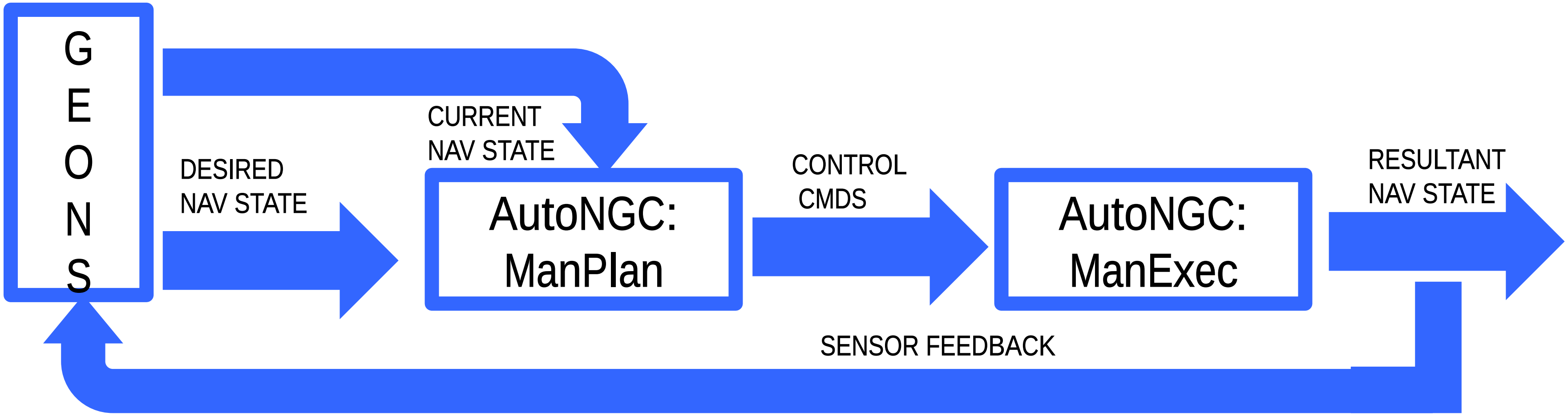
- Radiometrics: A measure of the change in a parameter associated with a radio frequency-based signal that can be used as an observable of direction, range, or relative velocity between two objects.
- As SCaN moves toward optical communications, the navigation systems will adapt and can benefit.



- Optimetrics: Same as radiometrics, but using an optical signal as the source to provide orders of magnitude increased accuracy on the observables

Autonomous Navigation, Guidance, Control

- Follow-on to onboard orbit estimation is onboard orbit control: autonomous maneuver planning, execution, and calibration
- AutoNGC demonstrated on EO-1 in 2000; Established for single mission
- Reduces ground ops required for maneuver planning and execution and associated risks
- Requires telemetry feed from the maneuver, similar to ground planning/execution/calibration process
- Algorithms for formation missions not yet implemented in FSW


GEONS

DESIRED NAV STATE

CURRENT NAV STATE

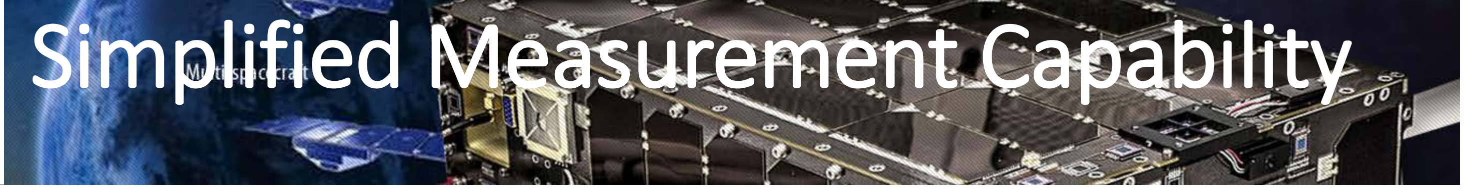
AutoNGC: ManPlan

CONTROL CMDS

AutoNGC: ManExec

RESULTANT NAV STATE

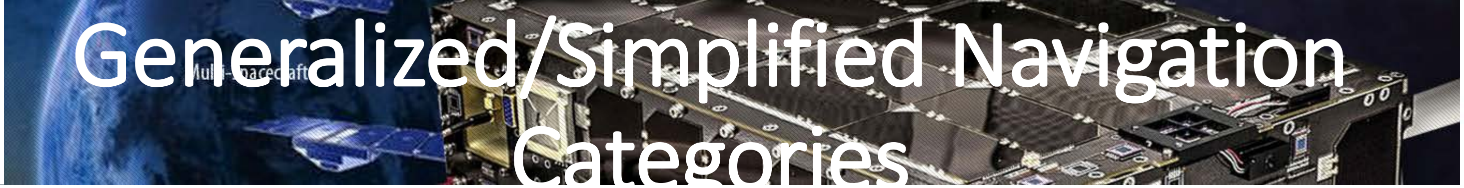
SENSOR FEEDBACK



Simplified Measurement Capability

- Broad summary of measurement capability
  - Not intended to indicate one size fits all
  - Some measurements not available in real-time
  - Snowflake-like possible combinations for performance & robustness

Orbit	GPS	TDRSS	NEN/DSN	ΔDOR (DSN)	CELNAV/Optical	Requirement/Source
LEO	50 cm @ 1 Hz	2–8 m @ 1.5 orbit	10–20 m @ 1.5 orbit	N/A	1 km @ 2 hr	≤ few m
HEO (perigee < 2Re)	10 m @ 1 Hz	100 m	100 m	N/A	0.1–15 km @ 1 orbit	< 1 km / many
GEO	5 m @ 1 Hz	N/E	100–200 m @ 36 hrs	N/A	1–5 km @ 1 orbit	10 m / many
Lunar, in view	N/A[a]	N/E	200m @ 2 days	1 km @ 1 day	0.5 km @ 0.5 days	500 m / LRO
Lunar, far side/hi lat	N/A	N/A	N/A	N/A	0.5 km @ 0.5 days	500 m / LRO
Sun-Earth L1/L2	N/A	N/A	2 km @ 3 wks	1 km @ 1 day	5–20 km @ 3 days	2 km / WMAP



Generalized/Simplified Navigation Categories

- Broad summary of navigation categories
  - Not intended to indicate one size fits all
  - More snowflakes
    - Mission unique elements
    - Combination of many known components

Category	Lower Accuracy	Accurate	High Accuracy	Precision Navigation
Absolute Definitive	100 – 300 m	5 – 40 m	50 cm – 10 m	< 1mm – 50 cm
Absolute Predictive (1 day)	1 km	75 – 500 m	5 – 50 m	5 cm – 5 m
Relative Definitive	1 – 50 m	1 – 10 m	0.1 – 1 m	<0.1 mm – 1 m
Relative Predictive (1 day)	<0.5 km	50 – 75 m	1 – 10 m	0.1 mm – 10 cm
Science Objective	Astro, Spatial, Loose temporal	Temporal, Surface Observer, Human	Temporal, Surface Observer/Altimetry, Human	Altimetry, Gravity, Interior Composition
Orbit Regime	Low, libration, helio cruise, cis-lunar cruise	Low, GEO, High, loose formation, precise maneuvers	Low, GEO, High, approach, formation, cluster	low, GEO, High, precise formation, rendezvous/docking

Planetary Navigation Summary

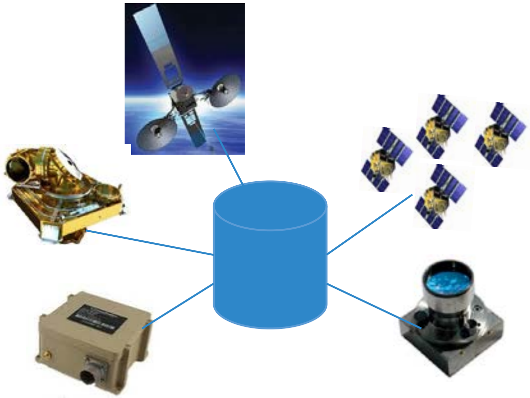
- Navigation in the near-earth regime, 2M km can be performed by a wide array of systems to provide robust solutions with seamless transitions between orbit regimes
- Navigation in the planetary regime has limited options with traditional ground support using radiometric tracking, onboard systems, and relative options available
- Many components within a communications system influence the resultant radio/optimetric tracking data quality
- GSFC Navigation offers relevant pre- and post-launch services to the user and networks communities
- Navigation needs to be an enabler for the science NASA hopes to achieve in the future – technology investments are key.

BACKUP

Sensors

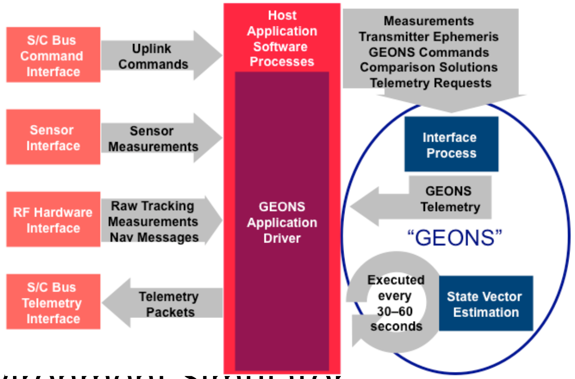
- GPS Receiver
  - GSFC developed weak-signal GPS; licensed to companies (BRE)
  - Assists in coverage in higher altitudes
- Global Navigation Satellite System (GNSS)
  - Advancing to additional signals (L2c, L5), including other constellations (Galileo, Glonass, Compass)
- Crosslink
  - Developed as element integrated with weak-signal GPS receiver to TRL 5 for MMS
  - 1-way range measurement for relative navigation
  - Low-rate data on signal (exchange science alerts, H&S, nav)
- Autonomous Rendezvous and Docking Sensor
- XNav sensor; translates pulsar timing to pseudo-range observation
- Star Sensor
- Accelerometer
- Integrate navigation sensor with communications receiver

Systems



- Fusion of multiple data types from independent systems
  - Robust to outages or shortcomings of any one system
  - High accuracy
  - Seamless transitions across orbit regimes
- GEONS flight software processes forward Doppler from ground stations and TDRSS, attitude sensor data for celestial nav, GPS, crosslink & TASS pseudo-range, XNav
  - Solves for absolute and relative navigation
  - Future data types: optimetric, optical imaging
  - Plans to upgrade to C++

Host Applications Use Their Own Driver to Access GEONS Methods



Host Application Software Processes

S/C Bus Command Interface

Uplink Commands

Sensor Interface

Sensor Measurements

RF Hardware Interface

Raw Tracking Measurements Nav Messages

S/C Bus Telemetry Interface

Telemetry Packets

GEONS Application Driver

Measurements Transmitter Ephemeris GEONS Commands Comparison Solutions Telemetry Requests

Interface Process

GEONS Telemetry

"GEONS"

Executed every 30–60 seconds

State Vector Estimation

- Test Facility: Formation Flying Test Bed
  - Provides Test As You Fly simulation capability
  - GPS simulator, Path Emulator for RF Signals, User Dynamics Environment Simulator
- From the spacecraft side, as comm subsystem is developed, nav and comm engineers need to work together to define requirements

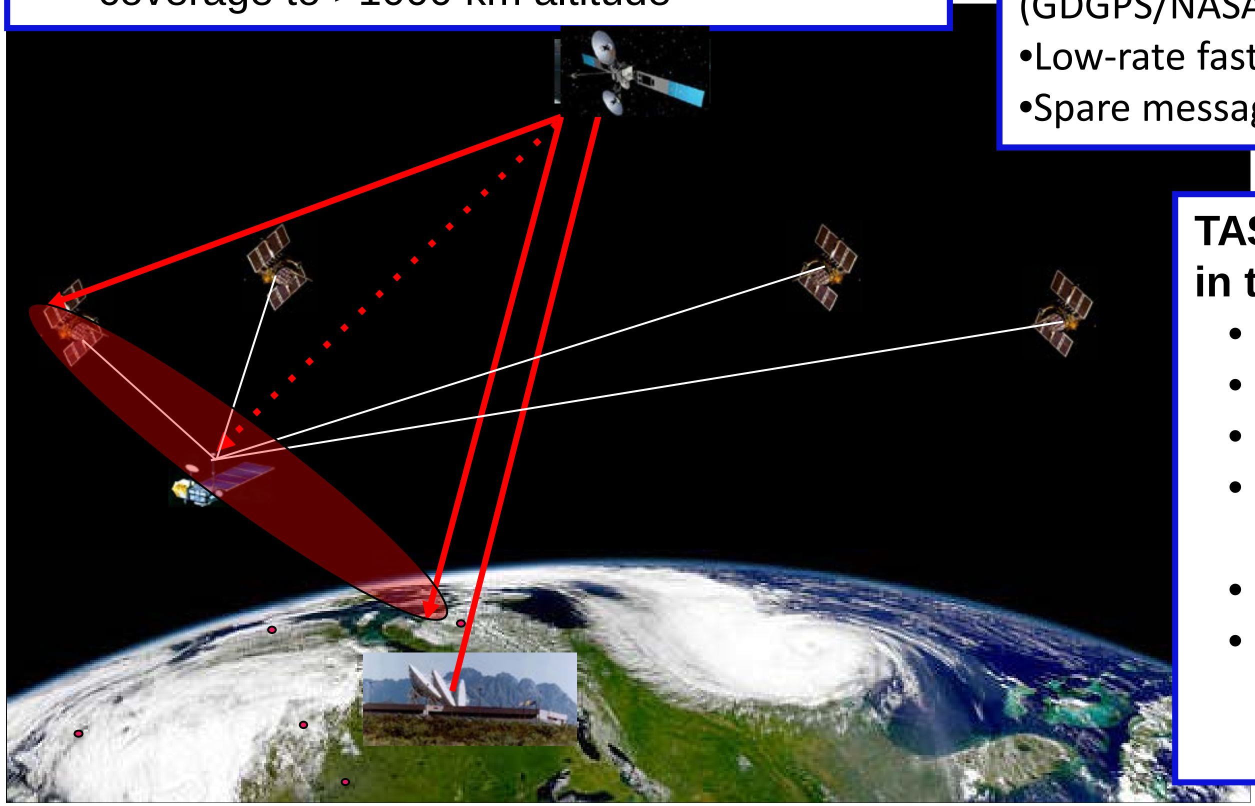
TDRSS Augmentation Service for Satellites (TASS)

TASS Signal Consists of:

- Low-rate data message (< 1 kbps)
- PN ranging code synchronized with GPS time
- A wide "earth coverage" beam transmitted from three TDRS locations to provide global coverage to >1000 km altitude

TASS Message Includes:

- TDRS ephemeris and health/status information (FDF, WSC)
- 0.5 Hz GPS corrections (GDGPS)
- 5 sec GPS integrity alarms (GDGPS)
- Data authentication (GDGPS)
- Earth orientation (GDGPS)
- Space environment/weather data (GDGPS/NASA GSFC CCMC)
- Low-rate fast-forward user commands (MOC)
- Spare message bits for future content



TASS provides direct benefits in the following areas:

- Science/payload missions
- Human Space Flight missions
- SCaN/Network operations
- GPS and TDRSS onboard navigation users
- TDRSS performance
- New capabilities consistent with the modern GNSS architecture