Applications and Mission Scenarios of Pulsar Based Navigation

593rd WE-Heraeus Seminar
Autonomous Spacecraft Navigation
New Concepts, Technologies, and Applications for the 21st Century
Physikzentrum Bad Honnef

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Presentation Objectives

- Introduction and Motivation
- Pulsar Sources
- Mission Requirements
- Applications and Mission Scenarios
- Challenges and Open Research Questions
- Future Endeavors

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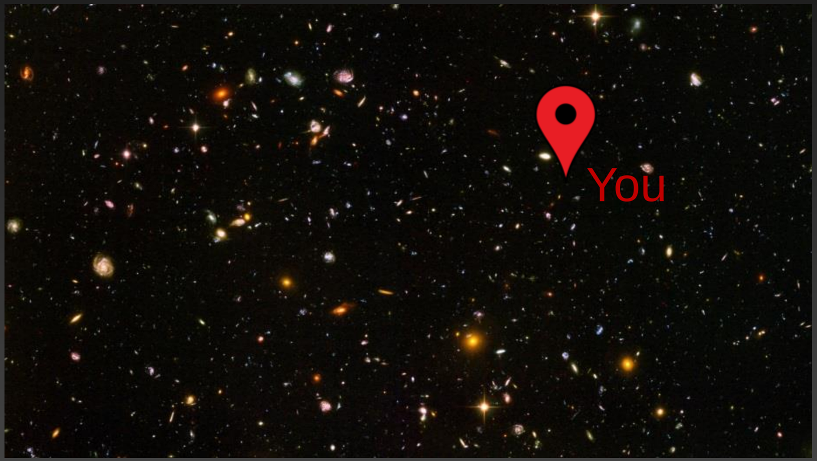
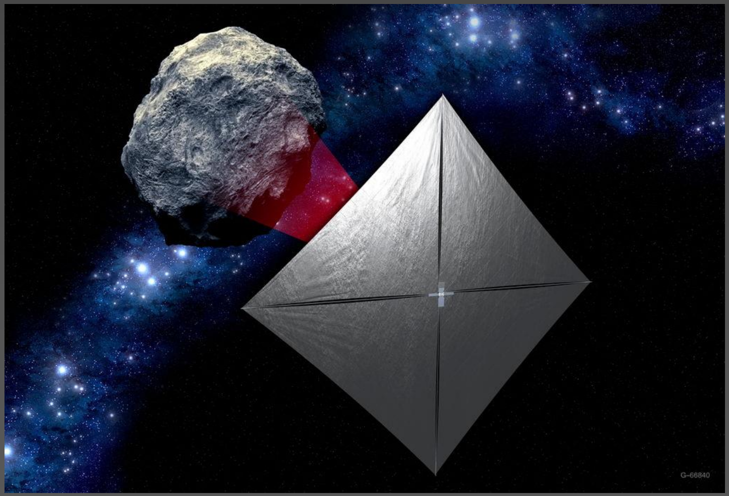
Spacecraft Navigation

- Navigation: Full 6DoF translation and rotation of spacecraft vehicle
  - Not just position
- Includes as necessary for a solution
  - Time — Clock corrections
  - Attitude — Orientation with respect to reference frame
  - Position — Absolute (SSB); Relative (previous reference point)
  - Velocity — Repeated position measurements

Enables farthest reaching applications and missions possible

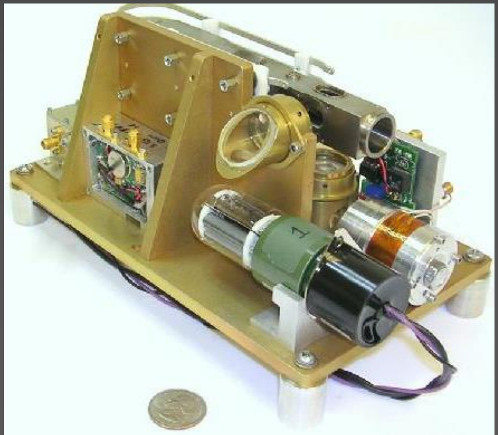




NASA

Current Methods
Time

- Typically, via Local Temperature-Controlled Oscillators onboard
- GNSS Time: ~10^{-12} (Allan Standard Deviation stability)
  - GPS (Rb, Cs); GLONASS (Cs); GALILEO (H, Rb)
  - For comparison, ultra-stable oscillators (USOs): ~10^{-11} to 10^{-13}
- Future Atomic Clocks
  - Push to use very good atomic clocks
    (eg. JPL DSAC: ~10^{-15}, ESA ACES: ~10^{-16})
  - Chipscale atomic clocks
    (eg. Honeywell CSAC, Microsemi CSAC: ~10^{-11})



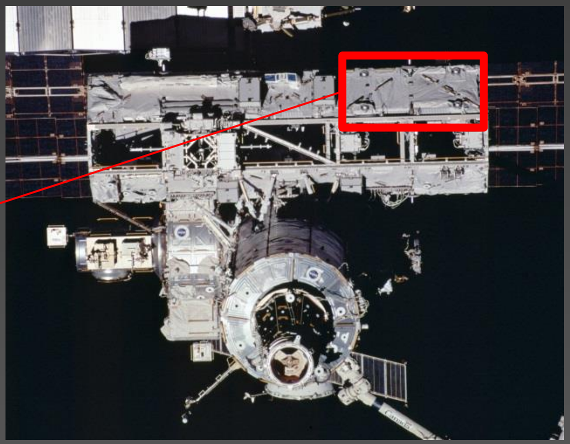
JPL, DSAC

Microsemi

Current Methods
Attitude

- Optical Star Cameras
  - Image scans of sky superimposed onto stored star maps
  - Complex system: star position table lookups, etc.
  - High SWaP and cost
  - Sun obscures Field of View
- Magnetometers
  - Orientation with respect to magnetic field
- IR Horizon Sensors
  - Sweep across Field of View, detect limb of Earth due to change in IR
- Sun Sensors
  - Angle through slits reflected onto photodetector
- GNSS Interferometry
  - Combine GPS with Rate Gyro Assemblies
  - Phase difference from delay at each antenna determines angle between antenna plane and satellite

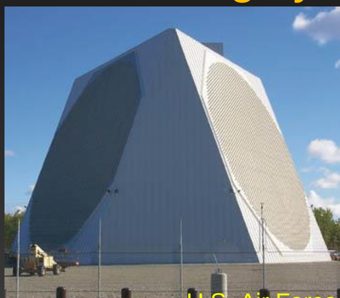
Stanford, GPB



NASA

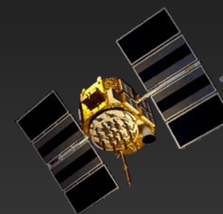
Current Methods
Position & Velocity Determination

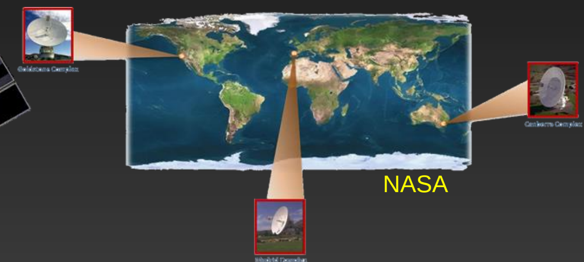
Largely Earth-based navigation for absolute position determination


U.S. Air Force


U.S. Air Force


Smithsonian/NASM

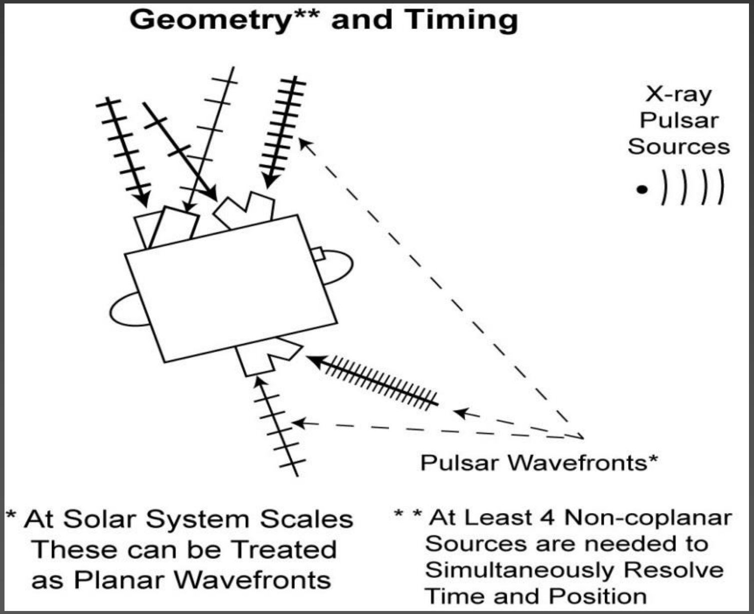



NASA

Radio Ranging	Optical Tracking	GNSS	DSN
Active hardware on spacecraft needed	Image compared to fixed star background	Can provide complete autonomous navigation solution	Radial position very accurate
Extensive ground operations	Position determined via image analysis	Only usable for near-Earth vehicle operation	Extensive ground operations and scheduling
Noisy background (electromagnetic)	Real-time measurements difficult	Availability decreases for ranges away from Earth	Angular uncertainty grows with distance
Position error estimation grows with distance from Earth	Environmental limitations		Position errors grow by as much as 10km/AU from Earth (DDOR 1km/AU)
Accurate planetary ephemeris needed	Imaging planetary bodies requires proximity to body		
Good ground station position knowledge needed	Costly onboard systems		

Pulsar-Based Precise Timing

- Monitor ultra-stable pulsar sources
  - Unique capability of providing atomic clock quality time
  - Not absolute time (no identifier in signal)
- Demonstrated with several sources
- Once position determined, time relative to arriving pulsar wavefront recovered from TOA
- Detection over long durations
  - Reduce onboard clock errors
- Stabilize long-term drift
- Potentially phase-locked loop for autonomous timekeeping (Hanson)
- Proper time to coordinate time comparison



CrossTrac Engineering

- Typically requires good position knowledge for accurate time determination

Pulsar-Based Attitude Instruments

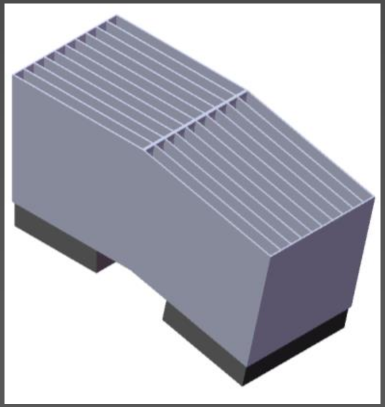
Imaging X-ray Star Camera

- Grazing incidence mirrors / Coded Mask
- Pixelated detector
- Guide star catalogue
- Like optical star camera

NASA GSFC

Collimated X-ray Star Scanner

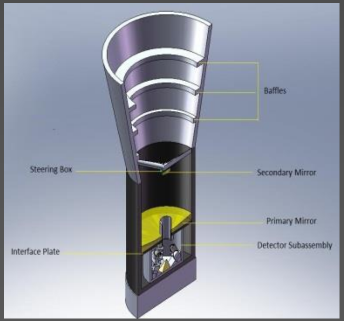
- Single fixed collimator or Differential collimator
- Spinning spacecraft
- Measure X-ray flux in given direction
- Create flux peak pattern
- Gimbal to scan sky
- Map of flux against gimbal angle or guide star catalogue



CrossTrac Engineering

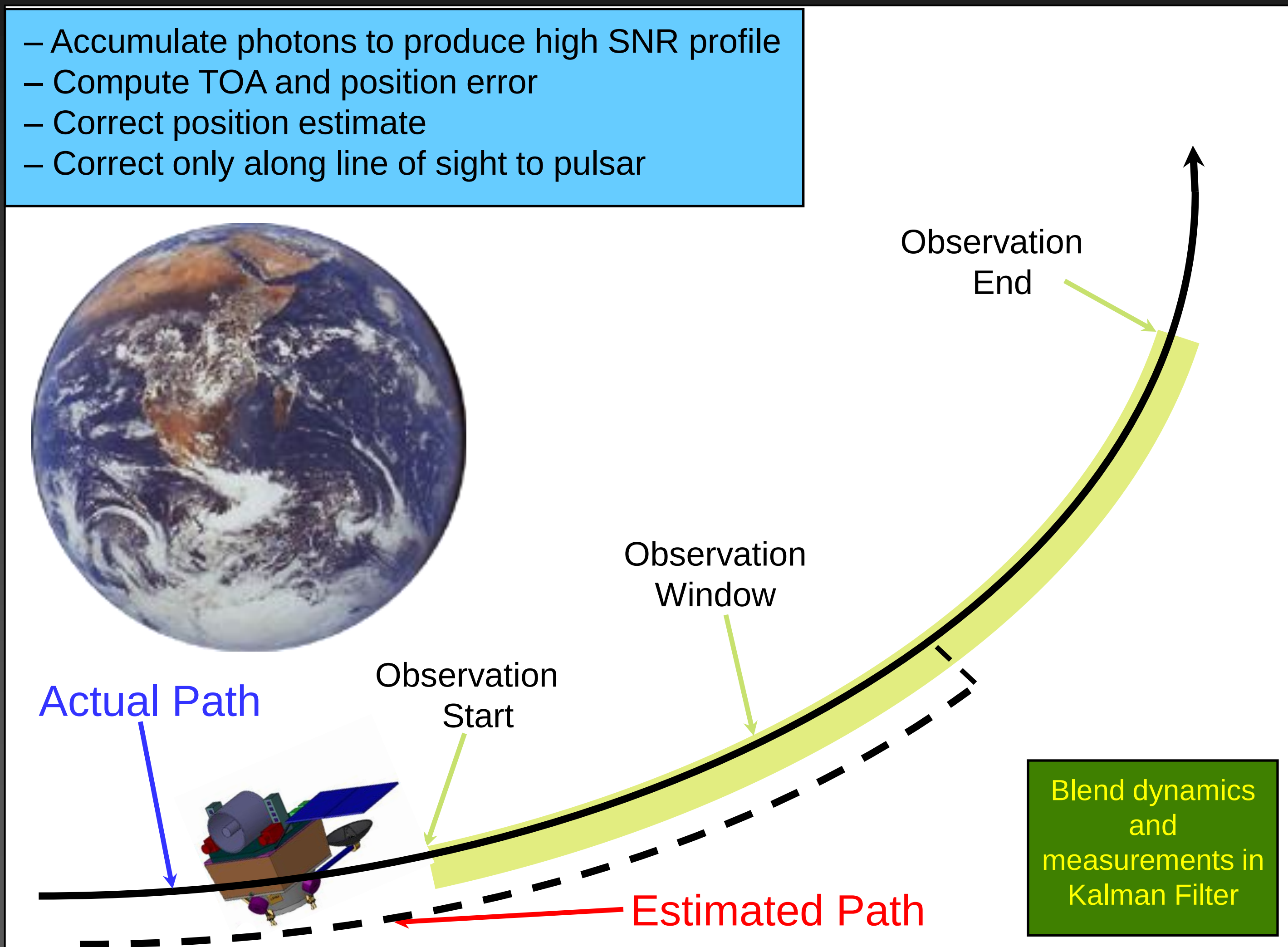
Reflected Type UV/ Soft X-ray Star Camera

- Star tracker concept
- Tracks single star in FOV
- Pyramid reflector to four detectors
- Narrow FOV (~ 1 deg)
- Movable secondary mirror to increase FOV
- UV reflecting optics
- Attitude determined by centroiding signal



CrossTrac Engineering

Pulsar-Based Position



Collect observed photons

↓

Compare pulse TOA to pulse timing model

↓

Set of solutions for different pulsar location

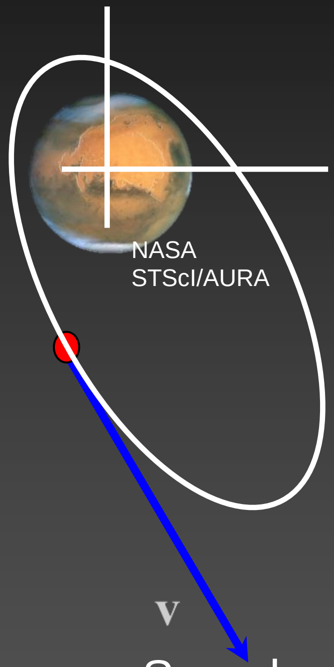
↓

Resolved position

Typically requires good timing knowledge

Pulsar-Based Velocity

- Velocity Determination
  - Methods
    - Orbit propagation
    - Repeated position measurements over time
      - Velocity is differential of position
      - Potentially amplifies noise
      - Less accuracy in velocity
    - Pulsar frequency Doppler shift
      - Doppler effects present in measured pulsar signals as vehicle moves toward or away from source
      - Compare measured pulse frequency to expected model to determine shift



Pulsar Navigation, DSN and GNSS Differences

	DSN	GNSS	Pulsar Navigation
System under human control	✓	✓	X
Exact transmitter position reported	X	✓	X
Clock steered to known time scale	✓	✓	X
One receiver track numerous observables	X	✓	X
Single transmitter trilaterate solution independently	✓	✓	X
Can complete full 6DoF navigation solution	X	✓	✓
Interplanetary and deep space capable	✓	X	✓

Goals for Evolving Spacecraft Navigation

- Allow for autonomous vehicle operation
- Augment existing systems
  - DSN & GNSS complement
- Wide operating range
  - LEO and GEO
  - Highly elliptical orbits
  - Interplanetary orbits
  - Someday ... Interstellar trajectory

…How do we apply these capabilities?

Motivation

1. *What are the future applications and mission scenarios using pulsars?*

2. *What are the challenges, specific to these applications, in practical implementation?*

3. *What are the future research areas that help mitigate and face challenges?*

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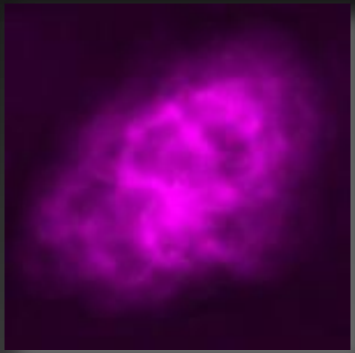
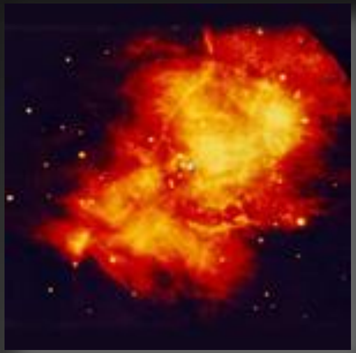
Source Energy Bands

Observations of Crab Nebula and Pulsar at Various Wavelengths

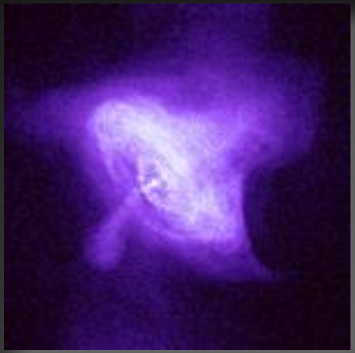


Radio
(VLA/NRAO)



Infrared
(2MASS/UMass/
IPAC-Caltech/NASA/NSF)

Visible
(Palomar Obs.)



X-ray
(NASA/CXC/SAO)

Practical implementation restrictions and considerations for each energy band

What are the pulsar sources lending to the forthcoming applications and mission scenarios?

- Optical
- Radio
- IR
- X-Ray
- Gamma-Ray

Optical, Radio: Requires large antenna: Issues of practicality for vehicle implementation → *Detectors, antennas*

X-Ray: Requires model assembly and almanac updates → *Processing*

Gamma-Ray: Sources are typically very faint → *Availability/Stability*

Pulsar Source Selection

Selection of source greatly affects spacecraft design and mission requirements:

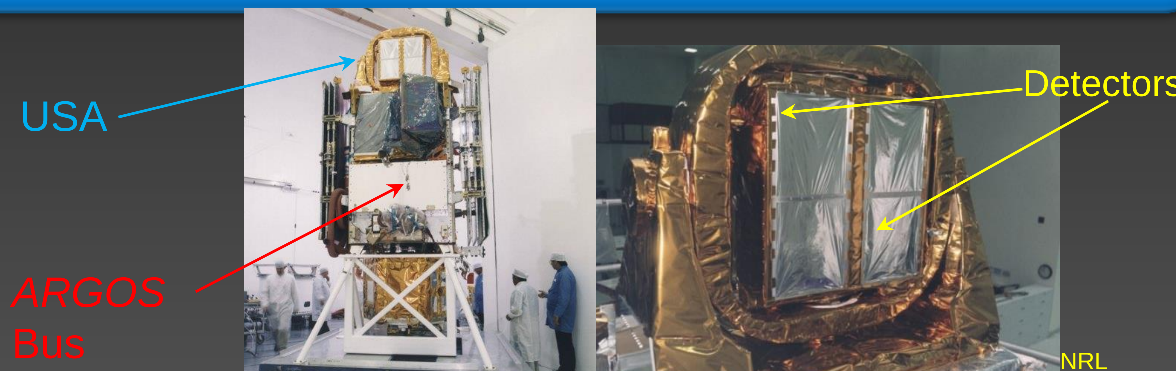
- ✓Practicality of implementation
- ✓Integrity of sources
- ✓Availability of sources
- ✓Reliability / Repeatability
- ✓Issues of jamming or spoofing navigation signal (security issues)

Pulsar Navigation Research

General Pulsar Research

1930's	Various	Theoretical predictions of neutron stars.
1967	A. Hewish & J. Bell	Discovery of radio pulsars*
1971	Reichley, Downs & Morris	Described using radio pulsars as clocks*
1974	Downs	Radio Pulsars for Interplanetary Navigation
1980	Downs and Reichley	Techniques for measuring arrival times of pulsars
1988	Wallace	Planned use of radio stars for all weather navigation

AND MANY OTHERS!



X-ray Pulsar

1981	Chester and Butman	Described spacecraft navigation using X-ray pulsars *
1993	Wood	Proposed vehicle attitude & navigation using X-ray pulsars*
1996	Hanson	Doctoral thesis on X-ray attitude determination
1999	USA NRL Experiment	Demonstrated X-ray source navigation
2004	Sala et. Al	ARIADNA report on pulsar timing for navigation
2005	Sheikh et. Al	Navigation using X-ray sources
2005	DARPA XNAV	Developed source characterizations, detectors, algorithms
2009	DARPA XTIM	Demonstrated pulsar use for time transfer

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Mission Requirements

- Driven by end user's chief priorities
  - Military Users
    (Coordinate land, sea, air, space operations)
    - Accurate time
    - Secure communications
    - Verification/validation of new clock technologies
  - Scientific Users
    (Fidelity of measurement and observations)
    - Enhanced observation techniques
    - Continued studies of variable celestial sources
    - Stability monitoring of existing time standards
  - Commercial & Non-Government Users
    (Reliability)
    - Repeatability and integrity of secure communications
      - E.g. financial data transfer

Reciprocal Beneficiaries

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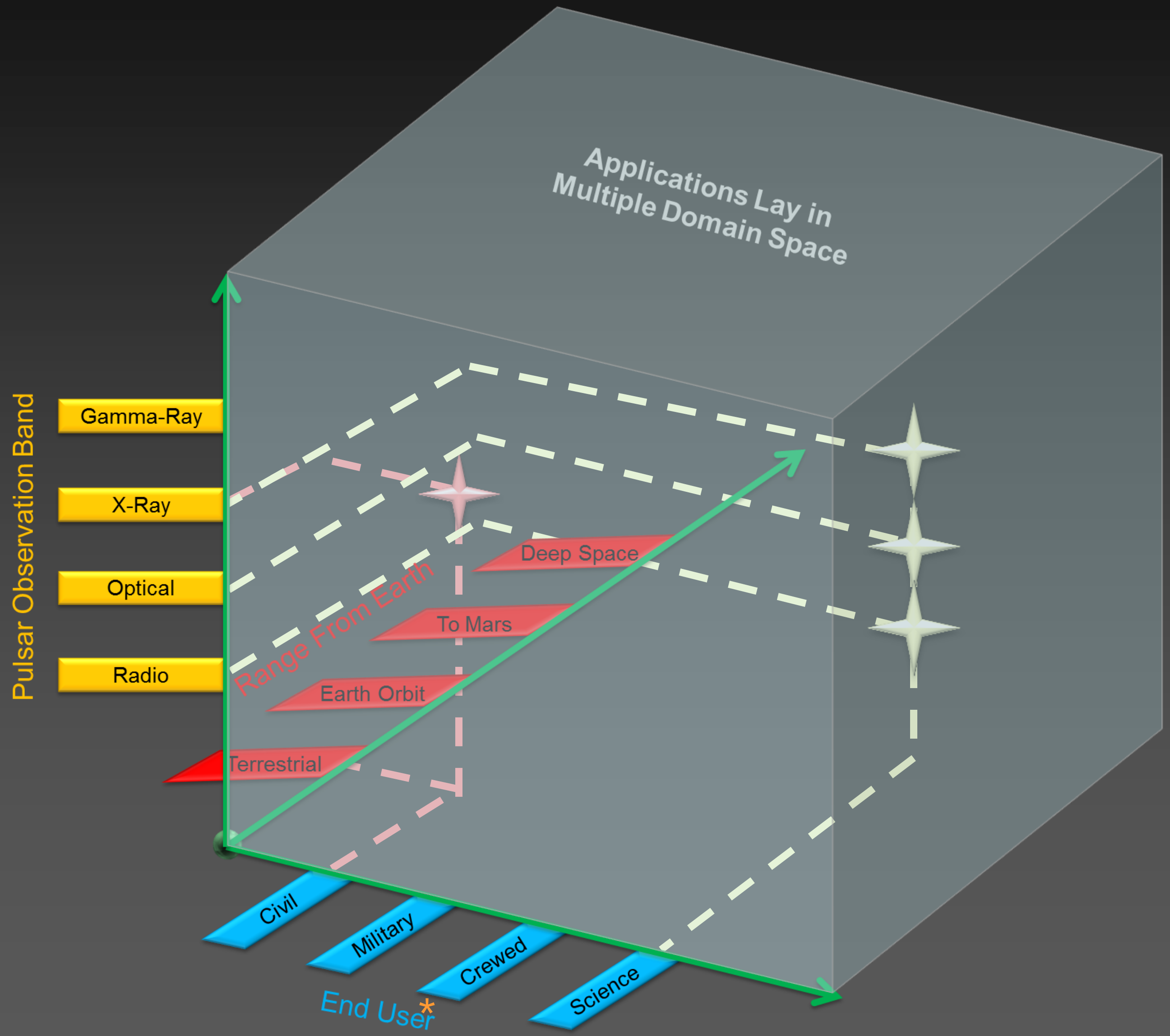
Applications and Mission Scenarios



Terrestrial Applications

- Pulsar Time Scale
- Long Term Timing and Signal Lock
- Very Long Baseline Interferometry: Earth-Based
- Clock Synchronization

Terrestrial

Pulsar Time Scale: Past Research

- International Telecommunication Union (ITU) (2003)
  - Opinion ITU-R 99
    - Observations (single & binary) important to astrophysics and timekeeping
    - Pulses measured via TOA to 1us
    - Pulsar lifetimes several million years long
    - Recommends universal pulsar time scale
    - Commonality to all observers
- A.E. Rodin (2005-2007)
  - Constructed ensemble PT using optimal Wiener filter
  - Comparable accuracy to Terrestrial Time TT
- G. Petit (2006)
  - IAU GA - Pulsars and Time Scales
  - Past Analysis: 1995 & 1996
    - Pulsar stability usable for long term stability of atomic scales
    - Flywheels to transfer current accuracy of atomic time to past and future

Terrestrial

160 A.E.Rodin

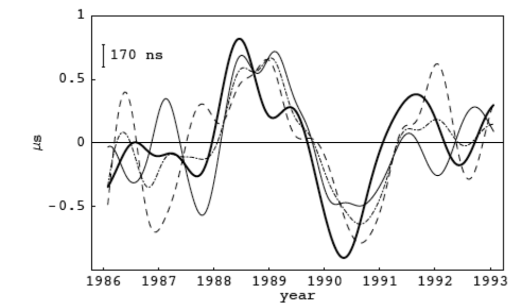
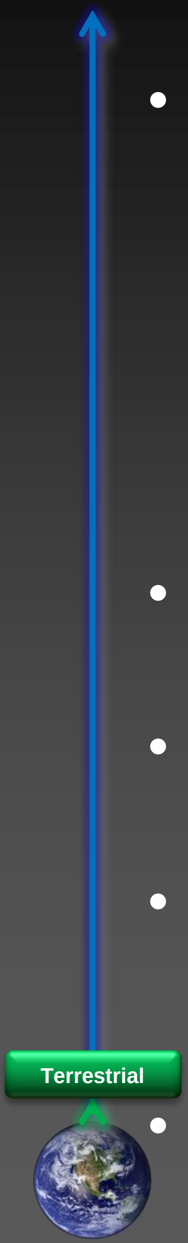


Fig. 2 Combined clock variations of UTC – PT in interval MJD= 46450 ÷ 48950 estimated using the optimal filtering method based on the timing residuals of pulsars PSR B1855+09 (thin line), PSR B1937+21 (dashed line), ensemble UTC – PT_{ens} (dot-dashed line) and UTC – TT (solid line).

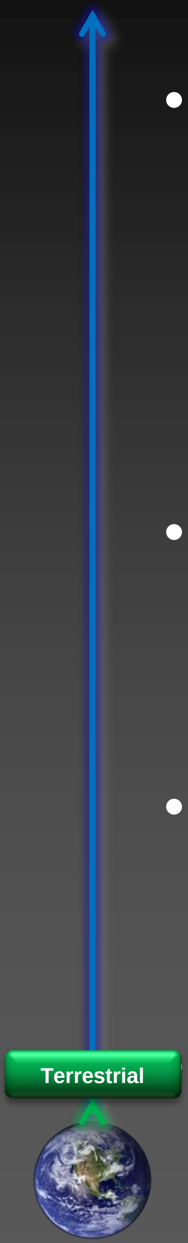
Alexander E. Rodin, "Alogrithm of Ensemble Pulsar Time," *Chinese Journal of Astronomy and Astrophysics*, Vol. 6, (Suppl. 2), 157-161 (2006).

Pulsar Time Scale: Approach



- Typically:
  - Time scale created with several stations around world
    - Different locations (NIST, USNO, BIPM), with different gravitational wells
    - Government or university stations fed time information
    - Create ensemble of based time, compared to established time (eg. UTC)
    - Can compare and convert to known terrestrial scale
    - Numerous clocks used to form
    - Stability over decades is difficult to measure and maintain
- Use ensemble of observed pulsars to generate Pulsar Time (PT) scale
- Pulsar TOAs measured to ~100 ns in ~1 hr observation
  - Not as good as atomic clocks, but can be maintained for long time
- Investigate long-term observed <u>radio</u> pulsars to evaluate good X-ray sources
  - E.g. B1937+21, B1855+09, J1713+0747, J0437-4715
- Create comparison and conversion to terrestrial time
  - (PT - UTC), (PT - TT)

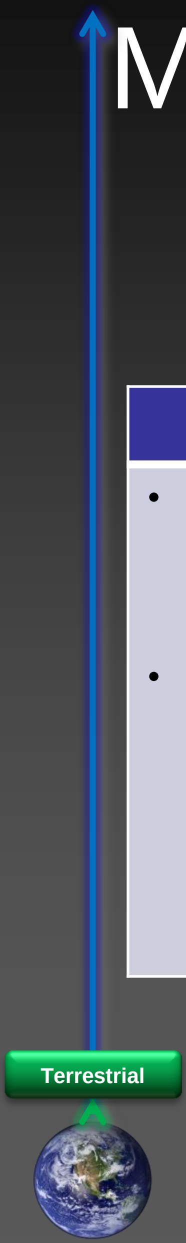
Pulsar Time Scale



- X-ray and radio pulsar signals
  - Frequency stability lends to PT creation
  - Possible to achieve short-term stability
    - Long-term pulsar observations + ultra-stable local clock
    - Timescale would be continuous and valid longer than any constructed clock
- Best method to define time scale: combine assets
  - Good short term clocks (Quartz Oscillators)
  - Short-medium term clocks (Rubidium, Cesium)
  - Group of MPSRs – for long-term time scale maintenance
- Scale creation: Assess several methods
  - Simple averaging
  - Phase-locked loop
  - Other filters (eg. Wiener, Kalman filters)
- Connected ensemble to terrestrial time scales
  - Non-Earth-based time scale
  - Can be maintained somewhere other than Earth (e.g. Mars)

Pulsar Time Scale: Mission-Enabling Characteristics

Stability	Autonomy	Universality
• Pulsar observation accuracy over long periods is very stable • Able to coordinate local atomic clock to pulsar ensemble	• Provide independent and precise time measure • Independent of regular communication to other users • Multiple users guaranteed access to same clock without inter-user communication	• Celestial source use • Any two users can correlate events on multiple spacecraft • Also can correlate on platforms not specifically designed for task • *Can be maintained somewhere other than Earth*



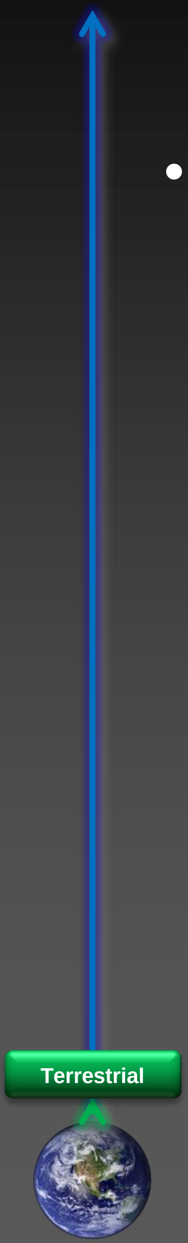
Long Term Signal Lock and Timing Control

- Primary purpose: Provide time for defense/military users and assets in event of catastrophic detonation or epidemic outbreak
  - Maintain communication/command signals & time amongst assets
  - Must be nuclear survivable
  - Operate and control system for specified amount of time post-event

- Time system approach (e.g. PT)
  - Atomic clocks on space vehicles
  - Master clock provides time for dissemination to all users (based on pulse stability from pulsars)
  - All other users *float* along with Master time
  - Not tied to specific Earth time scale
    - Addresses concerns of vulnerabilities to terrestrial-based time in emergencies

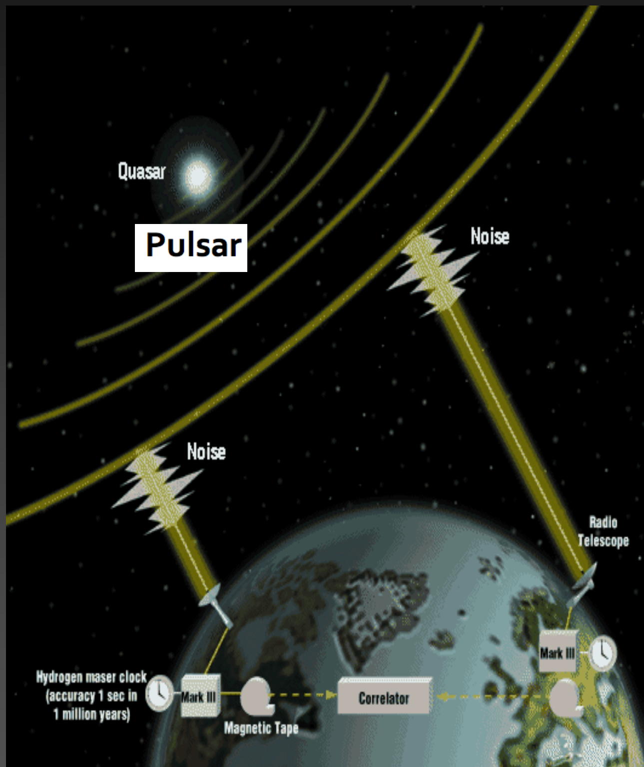
Terrestrial

Long Term Signal Lock and Timing Control (cont.)



- Enhance Long-Term Operation of Time Dissemination
  - Increase operational time for equipment
  - Military satellite communications operators need increased time to execute strategy
  - Operates for given amount of time after catastrophic event
  - Goal:
    - ***Provide months to years stability to military clock ensemble***
    - Augment/enhance existing capabilities
      - New system not needed
    - Added at the instrument-level
      - Direct Integration
      - Direct Control
  - Pulsar use highly germane: *No current method to autonomously steer atomic clock ensemble over the long-term*

Very Long Baseline Interferometry: Earth-Based



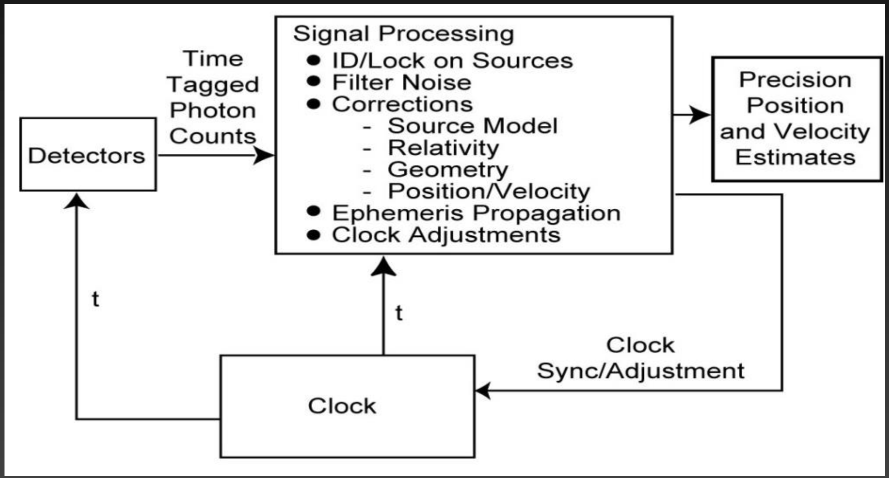
NASA

- Geodetic Technique: Widely separated antennae not connected by cables
  - Motions and orientation of Earth within defined inertial reference frame
  - Emulate much bigger array
  - Used to investigate distant sources or make simultaneous measurements
- Typically performed on both sides of Earth, such that source can be seen simultaneously by stations before orbit turns and source is removed from view
- Main Goal: All measurements of source must be precisely time synchronized
- XTIM: Considered pulsar signal being observed as the same <u>timing</u> source
  - Alternatively could have external measurement of pulsar timing
  - Clocks at different stations synchronized externally
- Application: Use pulsars to navigate spacecraft, such that when observing distant object, position and timing is precisely known
  - Only <u>time synchronization</u> is needed
  - However, on Earth, both sources could slew to view pulsar, then slew back to target object
  - <u>Remove common mode errors from both stations</u>

Terrestrial

Clock Synchronization

- Key component for operation of most coordinated systems
- Conditions
  - Source timing models
  - Good collection time
  - Good collection area
- Employ signal processing and filtering to produce very accurate time and range estimates
  - Spacecraft in Earth orbit
  - Interplanetary space
- Goal: Avert GNSS vulnerabilities that impact timing
  - Environmental / Accidental
  - Malicious



CrossTrac Engineering

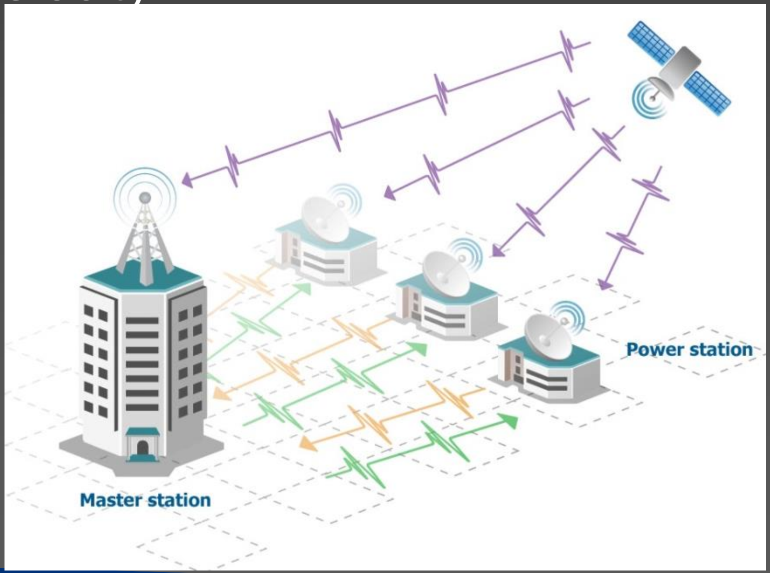
- Achieve clock adjustment
  - Corrects local clock driving detectors or other instruments
  - Enhances position and velocity estimates

Terrestrial

Clock Synchronization (cont.)

- Power Grid Timing
  - GNSS time syncs phasors in power plants and substations (common time source)
    - Measure electrical waves at remote points on grid
    - Ability to time electrical anomaly as propagates through grid
    - Trace location of power line break
  - Grids growing, makes models more complex
  - Concern: GNSS receivers' position-velocity-time solution may be vulnerable
    - Military, difficult to spoof
    - Civil, publically known and predictable
  - GNSS satellites coordinate time to master station
    - Constituent stations sync time to master and satellite
    - Coordinated time selection is key


CUNY

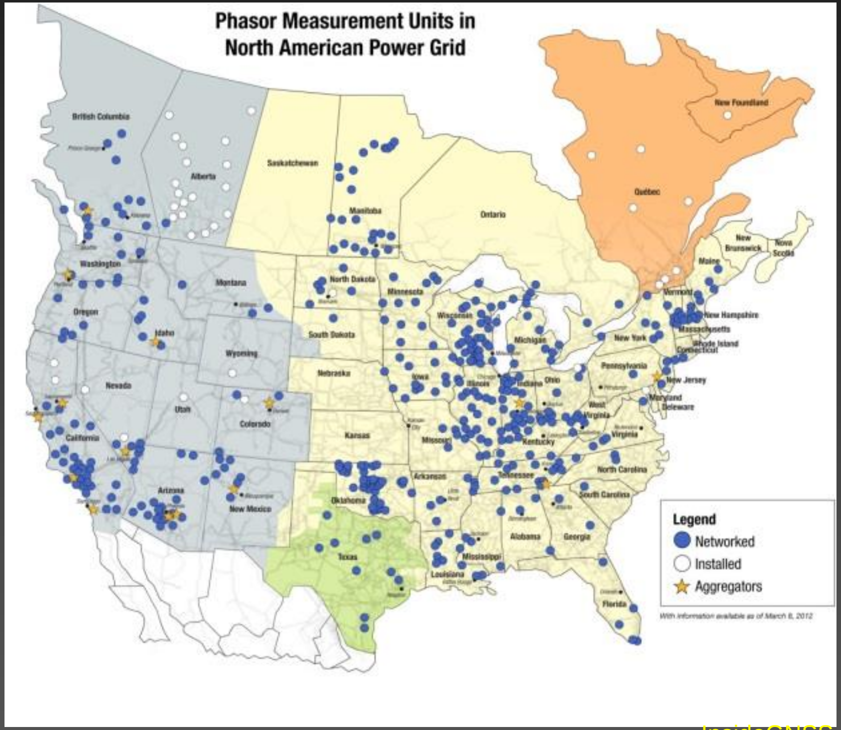


Advantech

Terrestrial

Clock Synchronization (cont.)

- Power Grid Timing (cont.)
  - Pulsar timing provides alternative to GNSS, highly stable time scale
    - Monitor and improve electrical power state
    - Efficient power transmission and distribution
    - Address increased frequency in blackouts:
      - Demonstrated need for improved time synchronization
    - Growing grids
  - Reduced susceptibility to jamming attempts
    - Environmental
    - Malicious



InsideGNSS

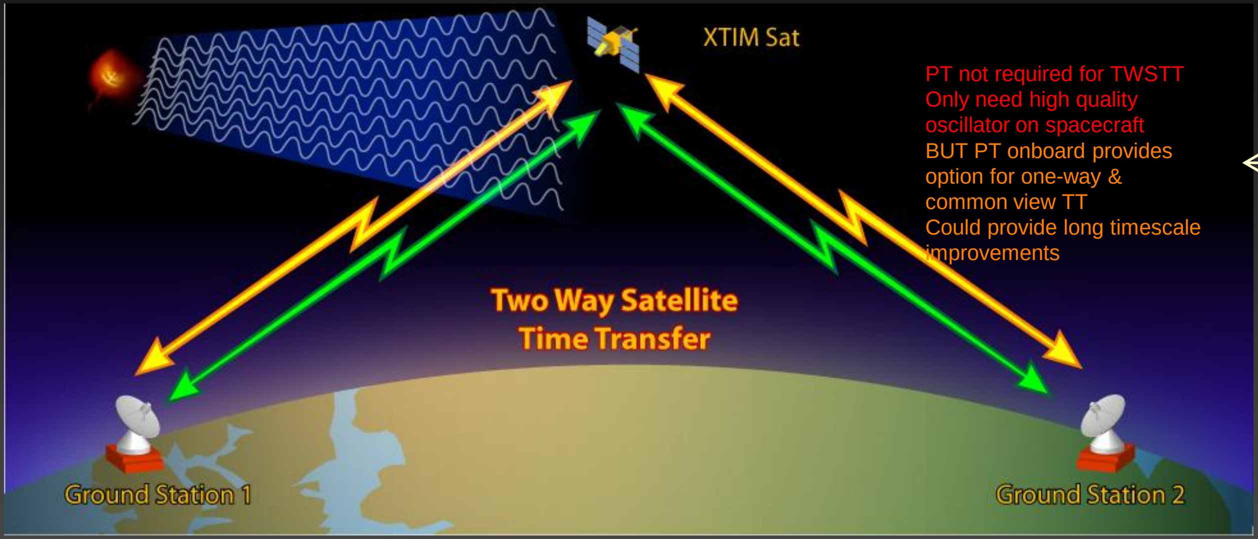
Terrestrial

Earth-Orbiting Applications

- One- and Two-way Satellite Time Transfer
- Passive Synthetic Aperture from Orbit
- Ground-Based Event Detection
- Time Transfer and Cross Linking
- Geosynchronous Orbit Maintenance and Ground Tracking

Earth Orbit

One- and Two-way Satellite Time Transfer



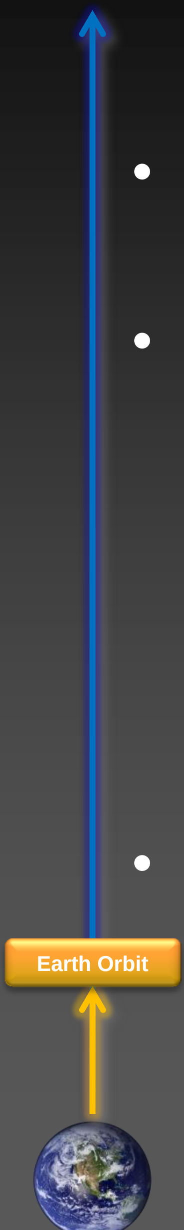
PT not required for TWSTT
Only need high quality oscillator on spacecraft
BUT PT onboard provides option for one-way & common view TT
Could provide long timescale improvements

Microcosm / XTIM

- TWTT: Transfer time between two clocks over large distances
  - Over horizon
- TWSTT: Use one spacecraft as relay station
  - Typically GEO communications satellite (E.g. DirecTV)
  - Usually commercial, civilian operated vehicles
  - *Receives precisely timed pulsar signal*
  - *Coordinates time to ground*

Earth Orbit

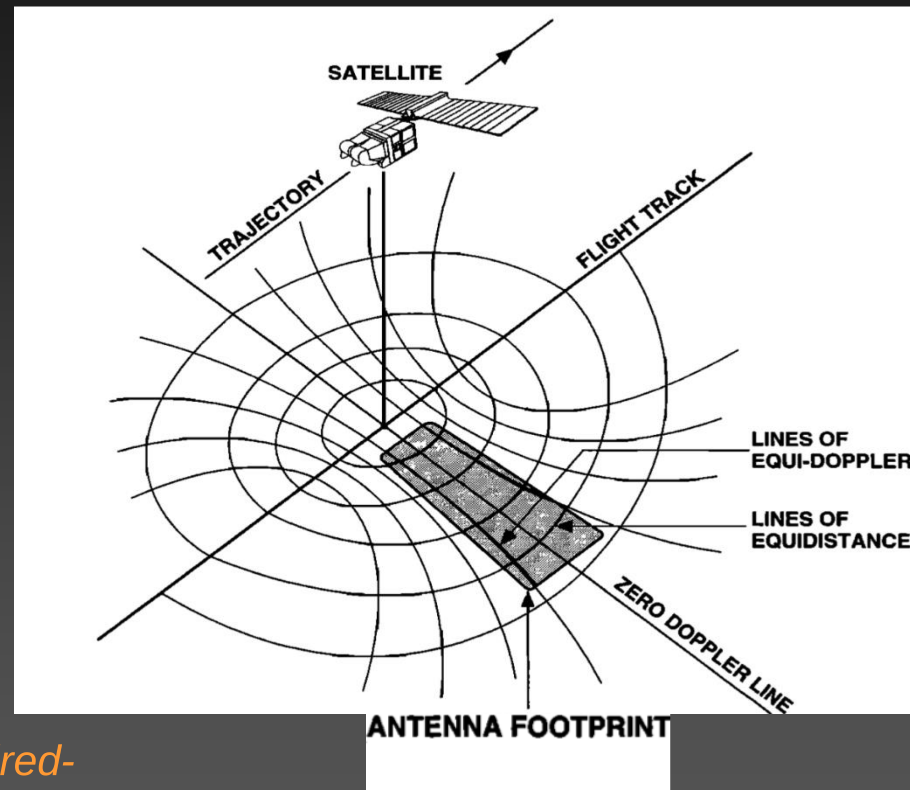
One- and Two-way Satellite Time Transfer (cont.)



- Traditional Challenges: Complex TX/RX at each station
  - Cost: Commercial operators pay for satellite time
- Benefits Support Precise Time Transfer to Expanded Users
  - Only a few users can employ TWSTT
  - Others rely on GPS Common View Time Transfer
    - Accuracy is ~1 nsec
    - **Goal: Provide 100 psec time transfer**
    - Potentially achievable with X-ray pulsars: stable source, calibrate errors
    - Source availability: Cost + Ultimate Performance
- Enhance Long-Term Control
  - Asset deployment with precise signal lock and timing control
    - **Potentially month to year signal stability**
  - Maintain cohesive common signal between separated assets
- Improve Navigation and Target Tracking

Passive Synthetic Aperture Radar from Orbit

- Distribution and strength of emitters on surface constructed from phase history at receiver as satellite moves.
- Example: *find sat-phone in Waziristan.*
- **Requires single satellite with accurate, stable time.**
- Similar to, but more computationally intensive than active synthetic aperture radar.
- Concept straightforward with inherently coherent signals (e.g., commercial radio).
- Broadband/pseudorandom signals also detectable if code is zero-crossing synchronous, or completely known.



Massonnet and Feigl 1998

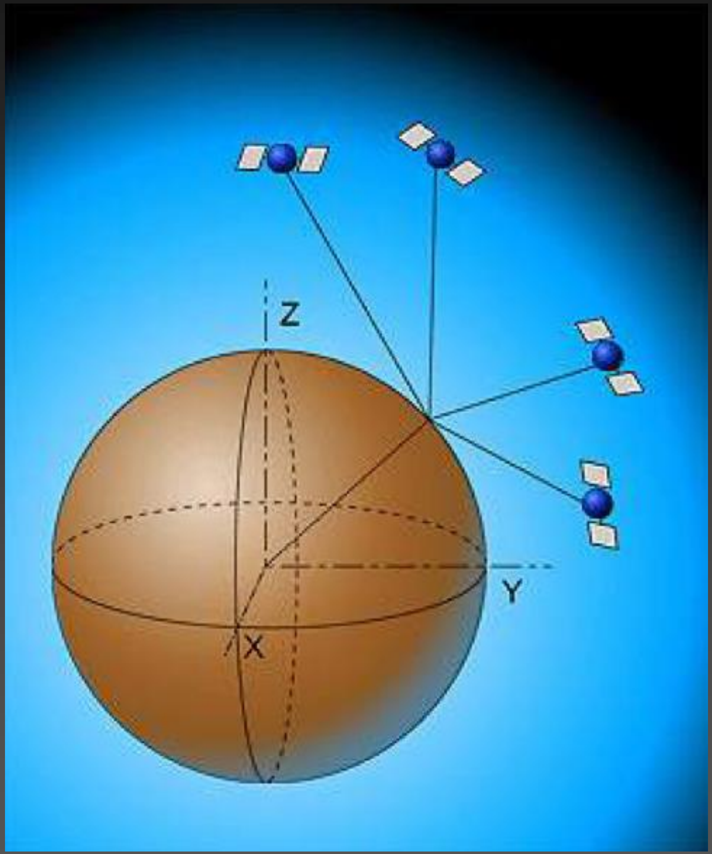
Earth Orbit

- ADVANTAGE: *Only one satellite required- determines timing from X-ray pulsars, observes ground active transmitters (or leakage?)*
- DISADVANTAGE: *Defeated by <u>unknown</u> non- zero-crossing-synchronous pseudorandom code.*

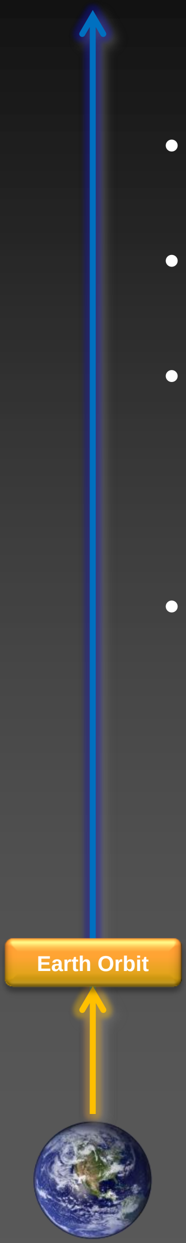
Richard Matzner, University of Texas, Austin

Ground-Based Event Detection

- Like "inverse GNSS"
- Randomly associated satellites
- Pulsars provide precise spacecraft locations and timing with respect to celestial source and terrestrial source
- Timing receipt at four satellites uniquely determines source event (location, time).
  - Possible event: radio signal
  - Possible event: *X-ray flash*
    - Detectable by satellites themselves
    - Nuclear events?
    - High voltage discharge?



XTIM



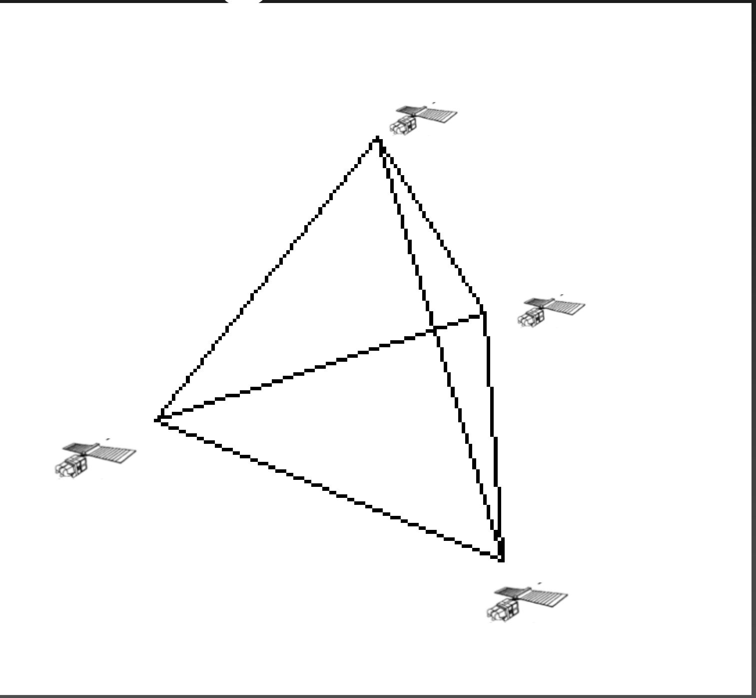
Spacecraft time can be transferred to ground based clock ensemble

Time Transfer and Cross Linking

- Four cross linked time- emitting satellites with onboard clocks produce a “rigid” array
  - — All sides known
  - — Orientation unknown

A) One satellite observes pulsars, determines PT. Relative transfer to other satellites is direct because all sides are known.

B)To determine orientation, all satellites must determine their own pulsar time. This time will have (periodic) offset from that of method A.



XTIM

Application: Virtual rigid telescope

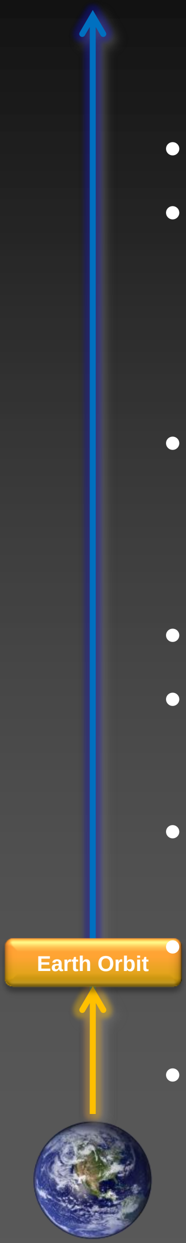
Earth Orbit

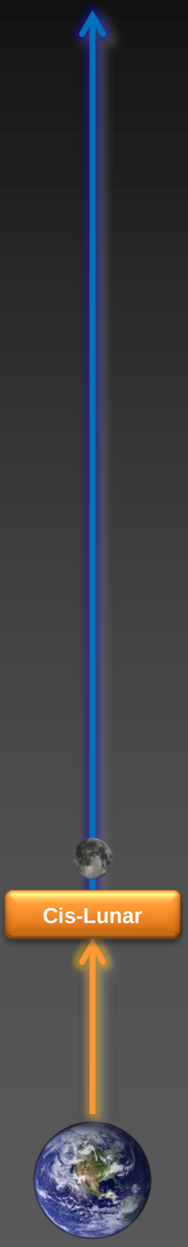
Geosynchronous Orbit Maintenance and Ground Tracking

- Frequent maneuvers
- Detection of unknown maneuvers
  - Latitude drift (Sun/Moon)
  - Small perturbations
- Quick recovery of accurate orbits with highly precise positioning and timing
- Key for reliable communication
- X-ray navigation use for accurate passage over ground station

TDRS, NASA

- Maintain positioning by frequent measurements of position
  - Area*time product
- DSN alleviation – reduce frequency of communication, antenna pointing
- Commercial operations cost reduction
  - *Fewer maneuvers*
  - *Longer spacecraft lifespan, reduced navigation load*

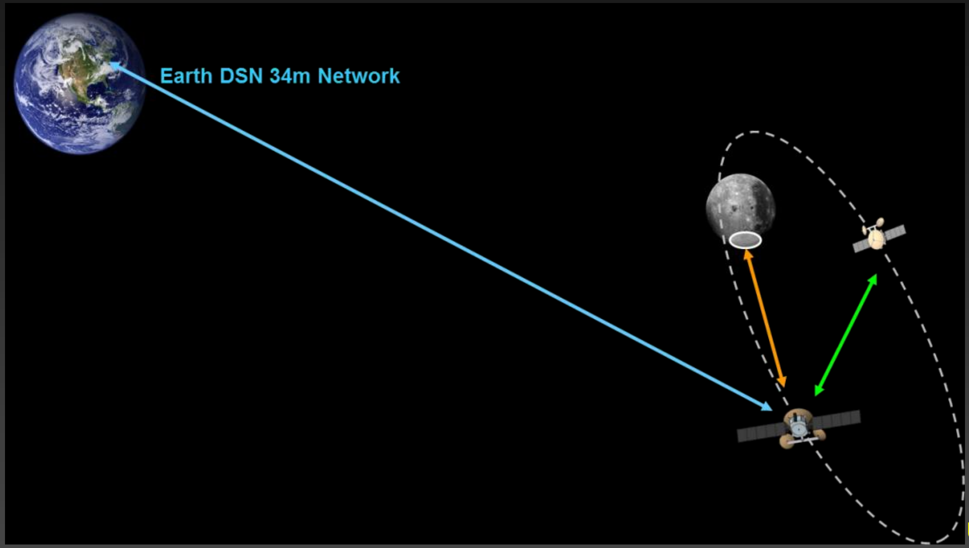




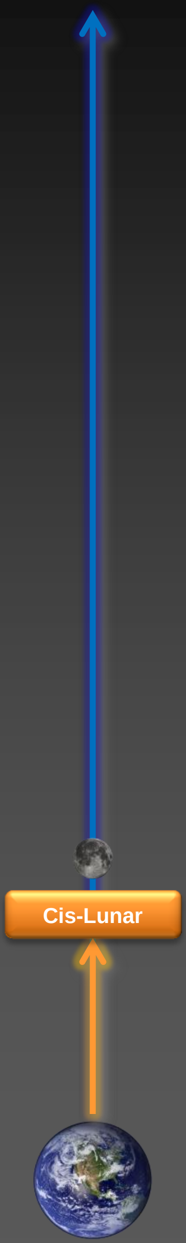
Cis-Lunar Applications

- Laser Communications for Lunar Satellites
- Relative Navigation for Lunar Communications

Communication Constellations for Lunar Stations

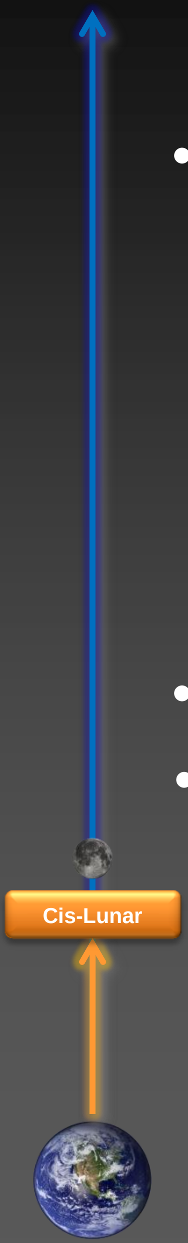


U. Colorado / LiAISON

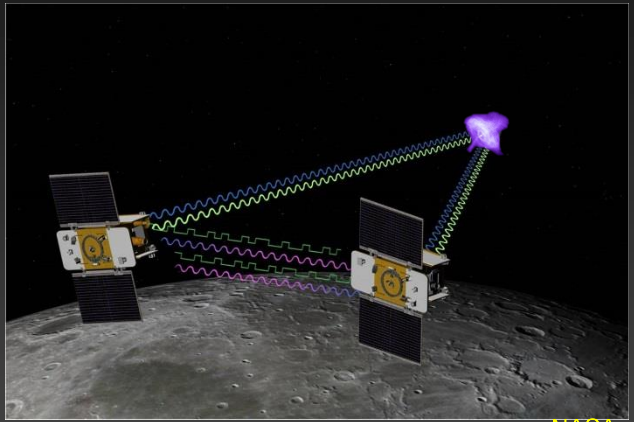


- Direct radio communication not always possible on moon
- Lunar relay satellite constellation communications and navigation
- Orbit, landing, and roving asset control
- Global coverage of lunar surface
- Robotic and human exploration
- Moon lacks atmosphere – X-rays can be detected at surface
- Pulsar navigation to autonomously maintain constellation orbit of communication satellites around moon
- Enables lunar surface exploration – or any planetary body
- Potentially self-timing network

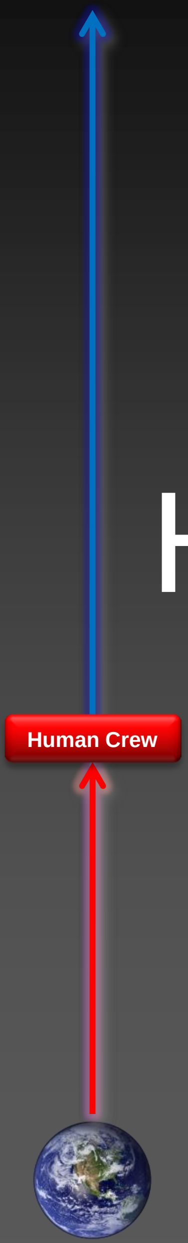
Relative Navigation for Lunar Communications



- Simultaneous observations of pulsar sources by two or more lunar orbiting platforms
  - (e.g. polar and equatorial)
  - Provides improved relative navigation performance


NASA

- Correlate observations from multiple spacecraft
- Benefits:
  - Supports navigation of individual spacecraft
  - No need for dedicated Earth communications link on smaller spacecraft
  - Smaller detectors
  - Alleviate DSN link for lunar constellation
    - Surface exploration



Human-Crewed Missions

- Human Space Stations
- Orion Mission
- Asteroids and Near-Earth Objects
- Space Tourism

Human Space Stations

- International Space Station
- Tiangong Space Station

- X-ray Pulsar-based Attitude Determination Complements GNSS
  - Star cameras already for backup
  - Antenna visibility
    - Pulsar techniques become higher in utility as auxiliary system when antennas obscured

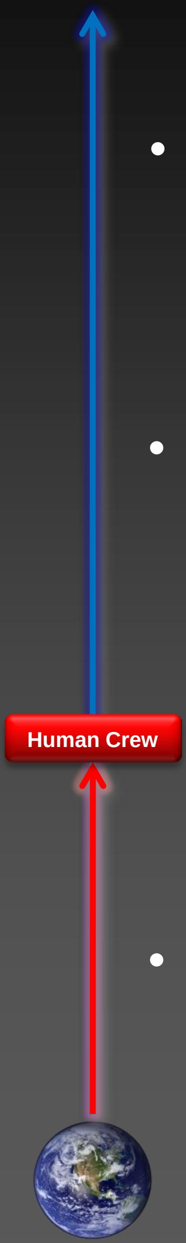
NASA

Human Crew

- Navigation Capabilities
  - Augment optical navigation for improved imagery

- ISS platform size conducive to larger detectors
  - Prohibitive on other smaller spacecraft

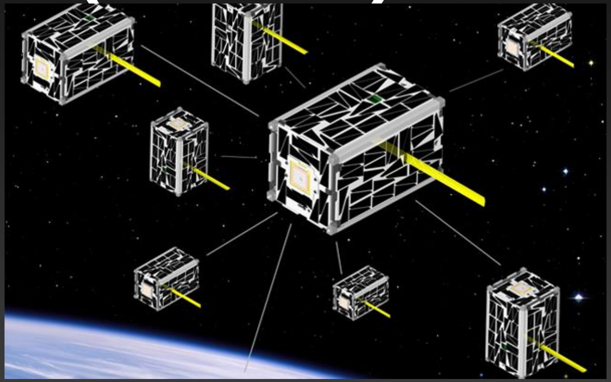
Asteroids and Near-Earth Objects



- Target object or asteroid terminal rendezvous guidance
  - (e.g. DAWN, WISE, Hayabusa 2)
  - Load-shedding for existing navigation technologies
- Hayabusa 2
  - Remote sensing instruments, lander, rover
  - Study asteroid 1999 JU3 from multiple angles
  - 2 High Gain Antennas for communication
    - Ka-band (downloading observation data)
    - X-band (daily data communications)
  - Navigation Instruments: 2 star trackers, 2 inertial reference units, 4 accelerometers, 4 sun sensors, optical cameras, LIDAR, target marker, laser range finding
- Pulsar navigation has potential to load shed for this and other missions with heavy attitude and navigation requirements
  - Rendezvous
  - Lander
  - Docking

JAXA

Asteroids and Near-Earth Objects (cont.)

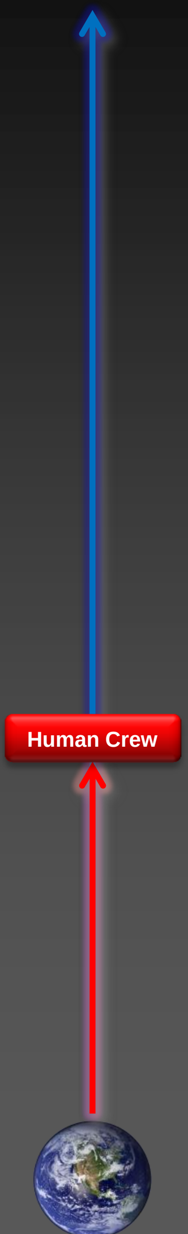


NASA

- Swarm navigation
  - CubeSat networks
    - Edison Demonstration of Smallsat Networks (EDSN)
  - Constituent swarm member signals combined to increase pulsar signal quality
  - Gravity Mapping
  - Mitigate issues with large antennas
    - Virtual node network of distributed antennas
    - Equivalent effective area (aggregate)
  - Challenges: Communication, signal processing, navigation solution determination over full network
    - Requires common virtual clock
- Mother-Daughter Scenario for relative navigation

Human Crew

Orion Mission



NASA

- Backup navigation to Moon, asteroid, or Mars
- Primary navigation for deep space?
  - Human Crewed missions require non-Earth-based system and <u>autonomous capabilities</u>
  - Reduce risk in communications, navigation, and data transmission
- Larger detector capable

Space Tourism

Human Crew

- Commercial crewed missions
- Space hotels

Bigelow Aerospace

- Reduced load for NASA – if tourism advances heavily
- Bigelow Aerospace – actively talking about space hotels
  - *Pulsars provide a navigation solution that does not tax the space communications infrastructure further*

Deep Space

Deep Space Missions

- Planetary Rover Navigation
- CubeSats
- Planetary Positions and Orbits
- Comet Tail or Dust Cloud Investigation
- Very Long Baseline Interferometry: Space-Based
- Sun-Earth Lagrangian Points
- Planetary Approaches
- Outer Planets and Deep Solar System
- Deep Space Relative Navigation
- Mars
- Solar Sail Concepts

Planetary Rover Navigation

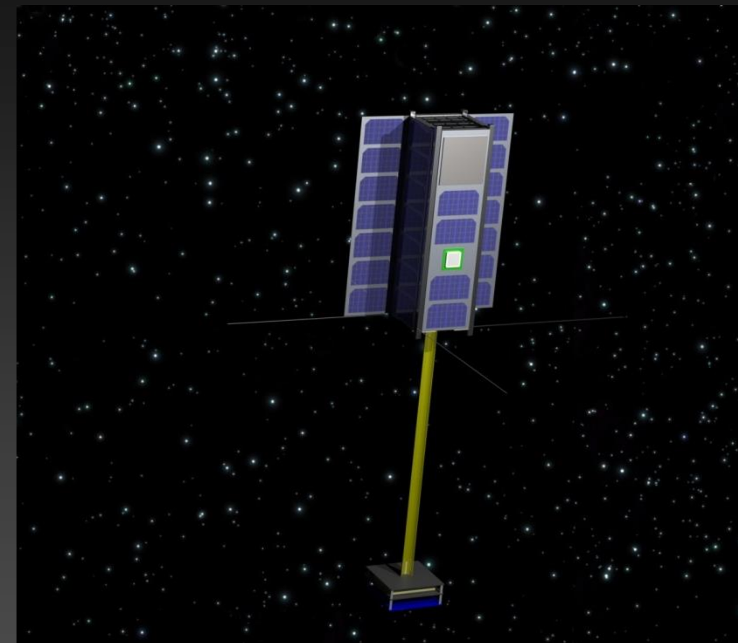
Deep Space

- For celestial bodies lacking an atmosphere
  - Mercury
  - Phobos, Deimos, Ganymede
- X-rays are observable (not impeded through atmosphere)
  - Key advantage: Allows smaller detectors
  - Integration to small roving or deployable vehicles
- Material samples from targeted areas
- Coordination between rovers
- Formation survey and mapping

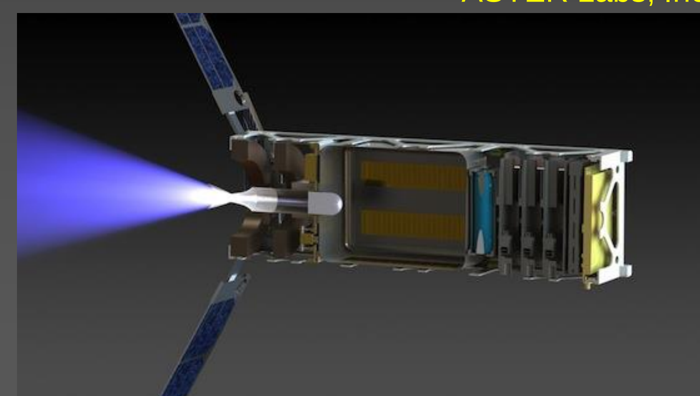
NASA/JPL

CubeSats

- To lower mission, launch, operations costs
  - Smaller vehicles trending
- New limitations on allowable SWaP envelope
  - Cannot practically employ large detector/antenna for radio sources
- X-ray photons detected by smaller detector modules possible
- Applications:
  - Object tagging in asteroid belt
    - Mining
    - Exploration
  - Interplanetary internet?



ASTER Labs, Inc.

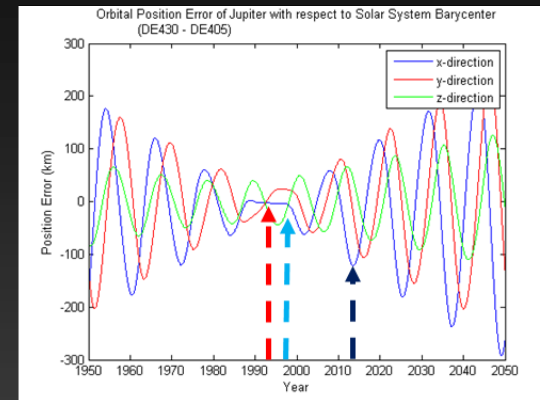


U. Michigan

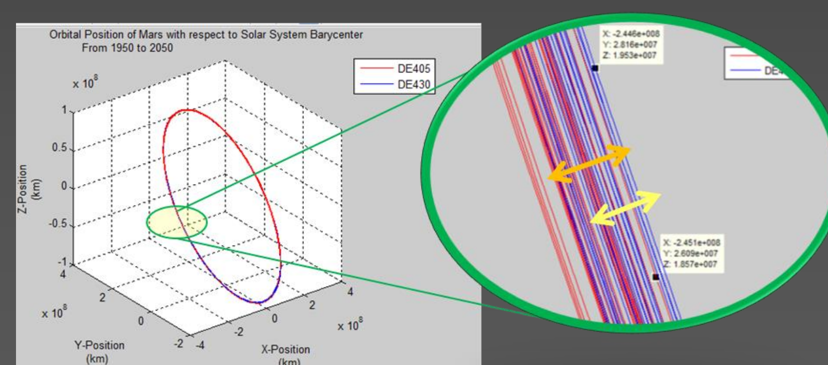
Planetary Positions and Orbits

Deep Space

- Accurate ephemerides required for good timing data for MPSRs
- Pulsars, inversely are viable for maintaining and improving planetary ephemerides
    - Independent pulsar measurements (e.g. via VLBI) with time-based positions
        - Fix orientation of Earth orbit (planetary frame) to pulsar frame
    - Pulsar timing over long span
        - Directly measure planet mass



Orbital positional error growth of Jupiter with respect to the Solar System Barycenter for DE430 – DE405 in three dimensions. The red dashed arrow is the initial implementation of DE403 and the ICRF. The light blue dashed arrow is the start of DE405, and the dark blue dashed arrow the start of DE430.

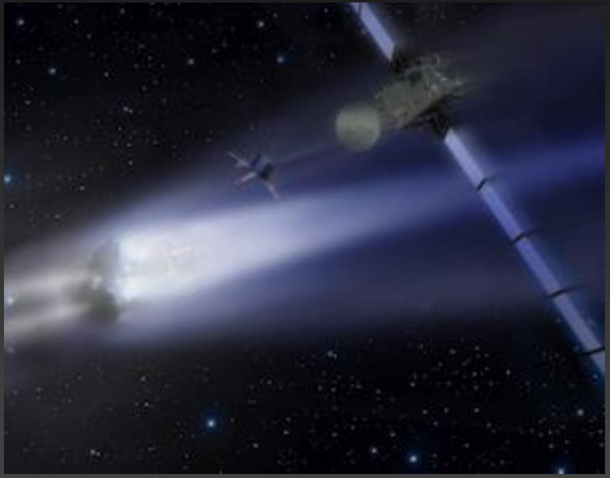


Position of Mars plotted and projected over 100 years using both DE405 and DE430 showing disagreements in location and changes in accuracy.

Comet Tail or Dust Cloud Investigation

Deep Space

- Precise rendezvous, formation flying, or surface exploration coordination via precise pulsar positioning and timing
- Orbiting pulsar-controlled spacecraft in precise communication and time synchronization with surface rover



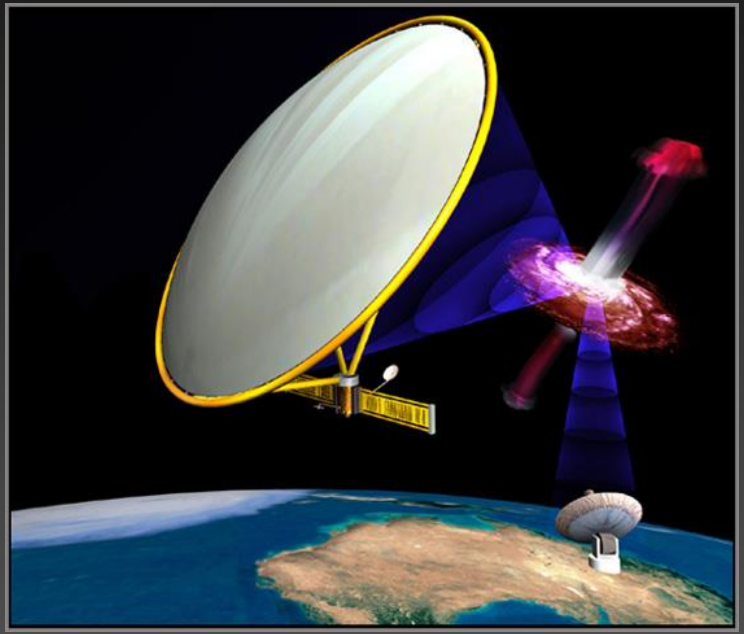
UCL

NASA/JPL

Very Long Baseline Interferometry: Space-Based

Deep Space

- First mission 1997-2003 VSOP (international)
  - 8m dish in elliptical orbit, up to 3X earth diameter
- Magnetospheric Multiscale Mission (MMS)
  - 4 identical spacecraft in tetrahedral formation separated by 10's – 100's of km
  - Study solar magnetosphere
  - Need to make coordinated observations
- Evolved Laser Interferometer Space Antenna (eLISA)
  - ESA observations of gravitational waves using laser interferometry
- Russian Spektr-R mission
  - Interferometric baselines of up to 350,000 km



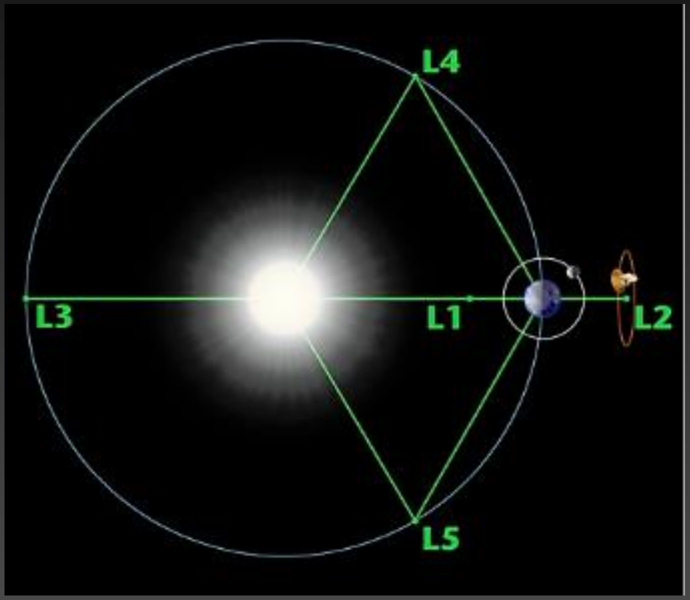
Fourth Millennium

Produce pulsar-based timing reference at spacecraft and contribute to ground based clock ensemble

Sun-Earth Lagrangian Points

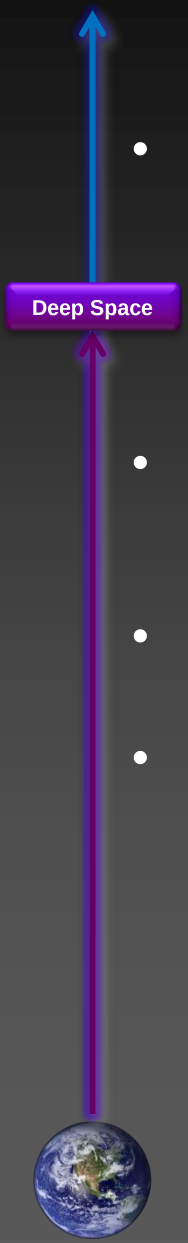
Deep Space

- L2 point: ~1.5 million km from Earth opposite Sun
- Stable orbits near L2
- Diverge after ~23 days without periodic maintenance
  - Wilkinson Microwave Anisotropy Probe (WMAP)
  - James Webb Space Telescope (JWST)



- Challenges:
  - DSN radiometric techniques give current baseline approach
  - Require regular, multi-hour updates for:
    - Tracking observations
    - Maneuver calculations
    - Ground commands
- Benefits:
  - Stable position relative to Earth
  - Minimal interference from Earth/Moon for celestial observations
  - Stable thermal environment
- Principal applications: (As missions proliferate and constellations add complexity)
  - Increased navigation autonomy and orbit maintenance
  - Reduced operations cost

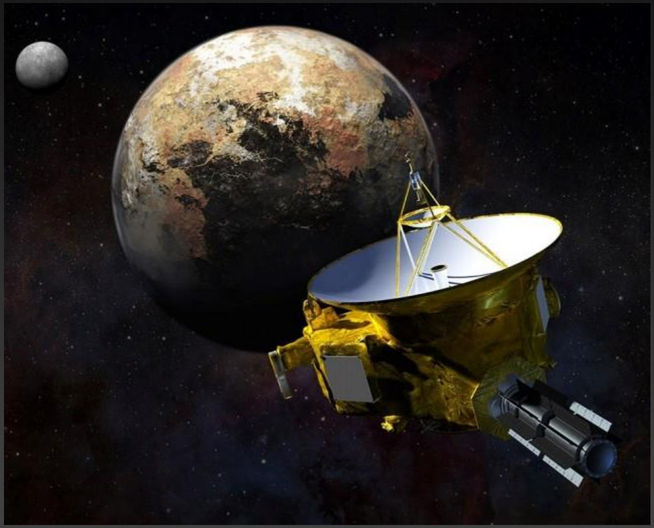
Planetary Approaches



- Current radiometric + optical methods near planetary destination proven very successful for NASA and ESA planetary missions

- Challenges:
  - Frequency of updates and ground commands
- Benefits:
  - Pulsar navigation for increased navigation autonomy and orbit maintenance
- Principal applications:
  - Enabling autonomous cruise phase with periodic course corrections
  - Primary navigation for all phases of orbiter missions lacking precision insertion requirements
  - Asteroid missions
  - Planetary landers

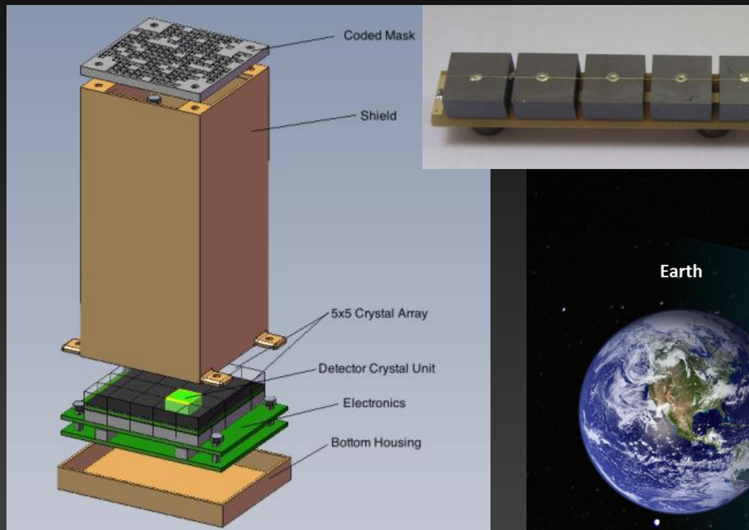
    Benefits cruise, but still require radar and/or optical instruments for final insertion/capture or landing (applies to the two items above)
  - Improve planetary ephemeris and gravity models
    - In conjunction with parallel Earth-based observations

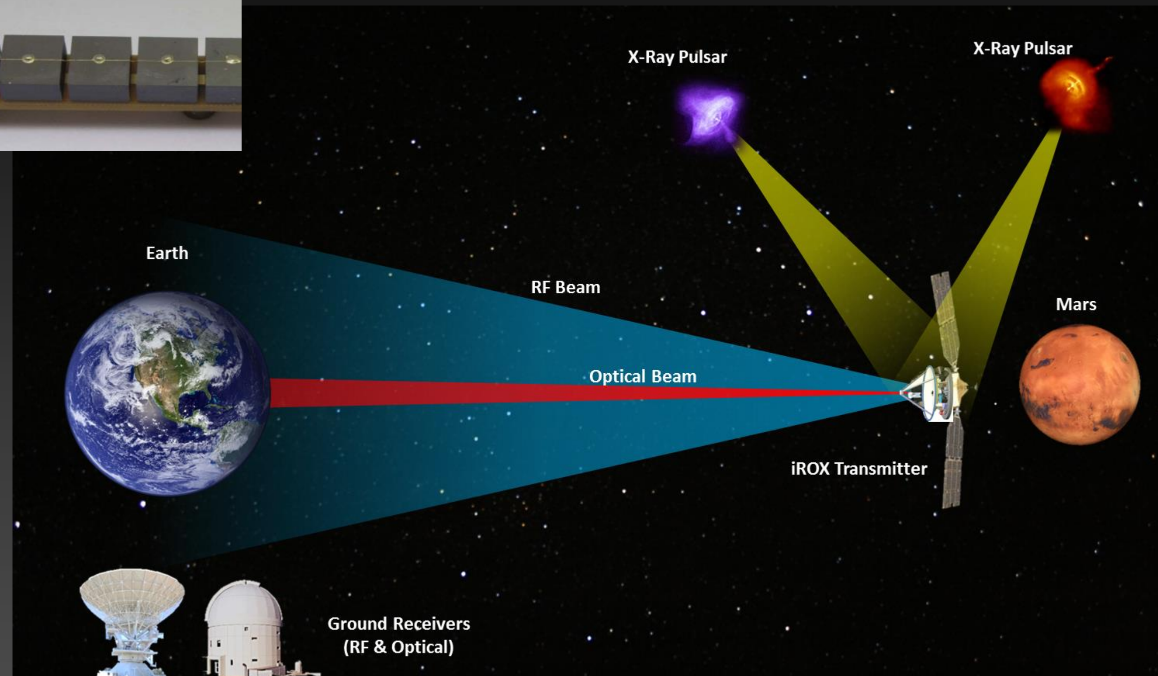


NASA

Mars Communications

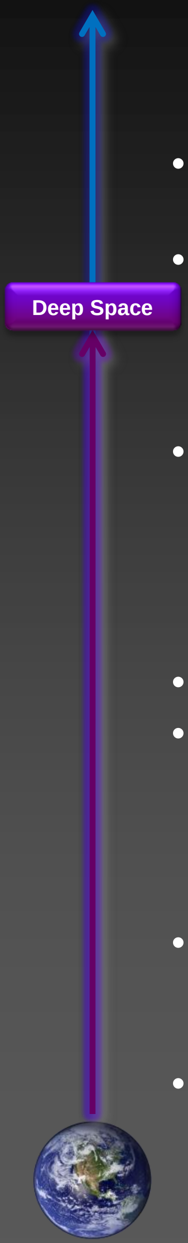
Deep Space





- Navigation at Mars
- Earth-Mars trajectories
- Precise pointing requirements at Mars to relay data communications
  - X-ray Attitude Determination
  - X-ray Communications
  - X-ray and Radio Pulsar Navigation
- Increased high data-rate spacecraft communications
- Hybridized spacecraft instrument: radio, optical, and X-ray
- High quality science data and high-definition video return
- Applicable for high-data rate, secure, non-jammable military networks

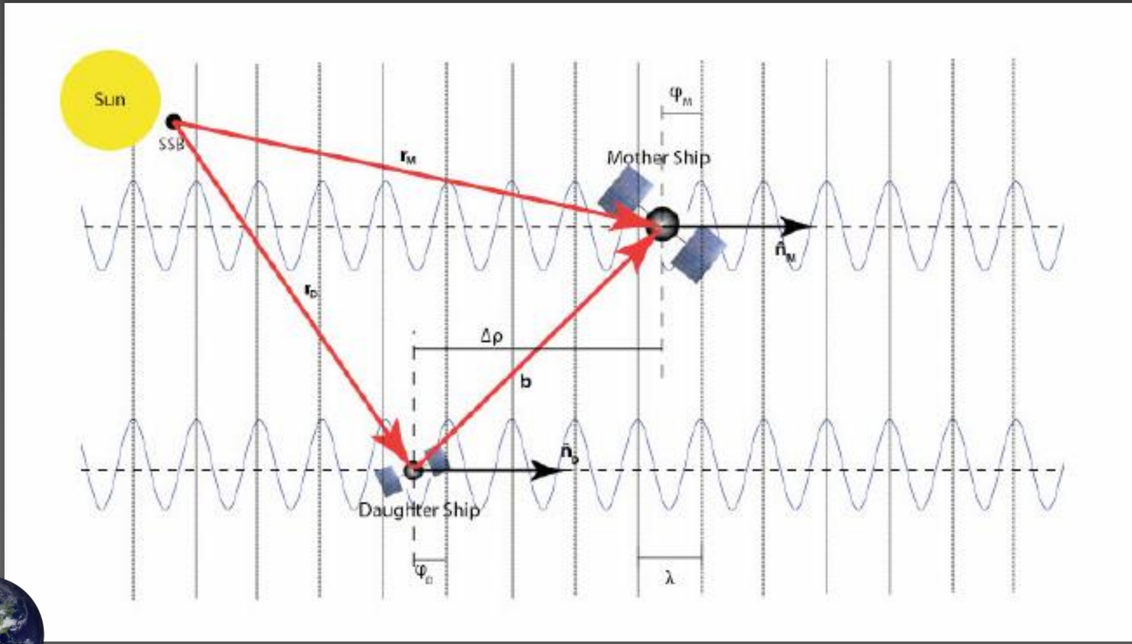
Outer Planets and Deep Solar System



- DSN tracking is very capable when not oversubscribed
  - Accurate to ~1nrad
- Pulsar navigation competitive in accuracy *in vicinity of distance to Jupiter* (~800 million km from Sun)
  - Distance from Earth oscillates from 700-990 million km
  - At Jupiter, DSN tracking accurate to ~1 km
- Potential <1 km accuracy with driving performance factors:
  - Sources
  - Detector
  - Observation time
  - Disturbance environment
- Comparable accuracy at solar system scale distances
- Example mission:
  - Verify Pioneer anomaly
    - Apparent deviation of Pioneer's anticipated trajectory from model predictions due to thermal energy creates small continuous thrust
- Benefits:
  - Increased navigation autonomy reduced operations cost
  - Potentially mission enabling for some applications
- Principal applications:
  - Enhanced navigation accuracy
  - Independent measurement from radiometric techniques

Deep Space Relative Navigation

- Allow for improved navigation accuracies using X-ray detectors with small effective collection areas
- *Mother-Daughter* scenario (akin to carrier phase differential GNSS)
  - *Mother ship*: space vehicle with large detector
  - *Daughter ships*: number of vehicles with smaller detectors
  - Navigation solution becomes position of daughter ships relative to mother ship



P. Doyle, U. Minnesota

Mother-Daughter scenario using X-ray signals (sinusoidal waves)

- Mother ship absolute position known
  - e.g. parked at Earth-Sun L1 operational base
  - e.g. satellite communications constellation

Deep Space Relative Navigation (cont.)

Deep Space

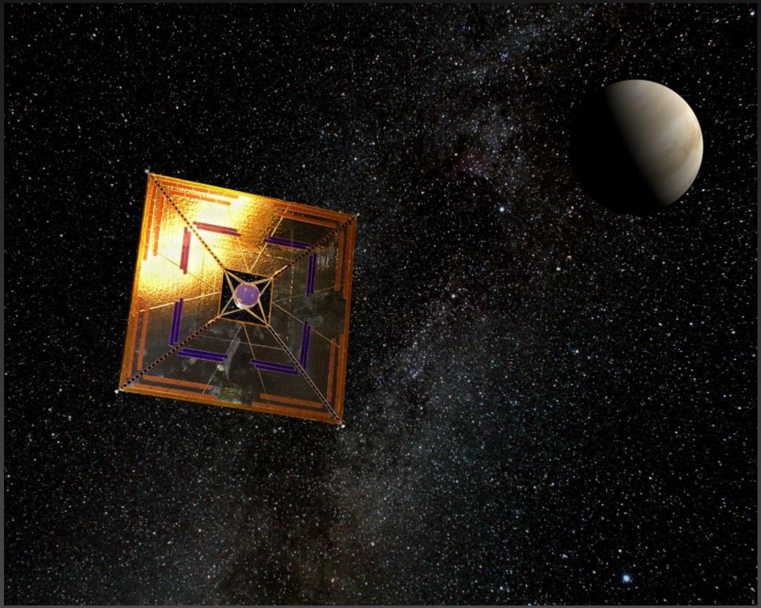
- Challenges are unique
  - Observables vector and measurement errors very different than GNSS carrier phase
  - Three principal challenges:

Time Series Model Formation	Operational Considerations	Time Synchronization and Errors
• Large detectors with long observation times - Time series model can be developed • Small detectors - Background photon flux overwhelms pulsar signal - Not possible to construct complete picture of time series of received photon history	• Pulsar geometry quality • Sufficient signal reception for calculating relative range • Data communication bandwidth requirements - Power and communication budgets of small spacecraft	• GNSS algorithms assume observables received are time-stamped and Mother-Daughter detector measurements can be synchronized • But X-ray pulsars are not deterministic and not generated by a GNSS-like transmitter

Solar Sail Concepts

Deep Space

- 1976: JPL design
- IKAROS (Japan): first to successfully demonstrate
  - Attitude via Sun Sensor and Doppler modulation of downlink RF due to vehicle rotation
  - **Complete spin axis attitude determination only possible during ground contact
    - Processed on the ground
    - Ground-based Doppler
- Operational Corrections and Maneuvers
  - Correct small errors in solar panel trajectory corrections
  - Interstellar flight navigation
  - Oort Cloud navigation
- Missions
  - Kuiper Belt Fly-through
  - Outer solar system rendezvous missions
    - Reduce durations for orbit maneuvers when farther from Sun
  - Flyby missions beyond Neptune



NASA

DARPA 100-Year Starship

"To Infinity and Beyond!"…

- DARPA & NASA grant program
- Funding of business plans to develop business plans for initiatives for interstellar travel in the next 100 years.

- Energy
- Equipment
- Materials
- Food & Water
- *Concepts for navigation…*

Presentation Objectives

- Introduction and Motivation
- Pulsar Sources
- Mission Requirements
- Applications and Mission Scenarios
- **Challenges and Open Research Questions**
- Future Endeavors

Challenges and Open Research Questions

- Detector sizes
  - Concepts evolving but area*time product limitations remain
  - Collimators, coded apertures, concentrators designed
- Almanac maintenance and dissemination
  - Pulsar timing model formation
- Intrinsic noise levels (instrument)
  - Limit timekeeping
  - Limit positional accuracy
- Source Characterizations
  - Few MSPs adequately investigated for X-ray ms pulsations
- New investigations into complex phenomena
  - Faintness, transients, flaring, bursting, glitching
- External noise from X-ray background, cosmic ray events
- Tradeoff of optimizing area*time vs available payload SWaP
- Tradeoff of bright sources with less stability
- Onboard stable clocks – cost factor

Presentation Objectives

- Introduction and Motivation
- Pulsar Sources
- Mission Requirements
- Applications and Mission Scenarios
- Challenges and Open Research Questions
- **Future Endeavors**

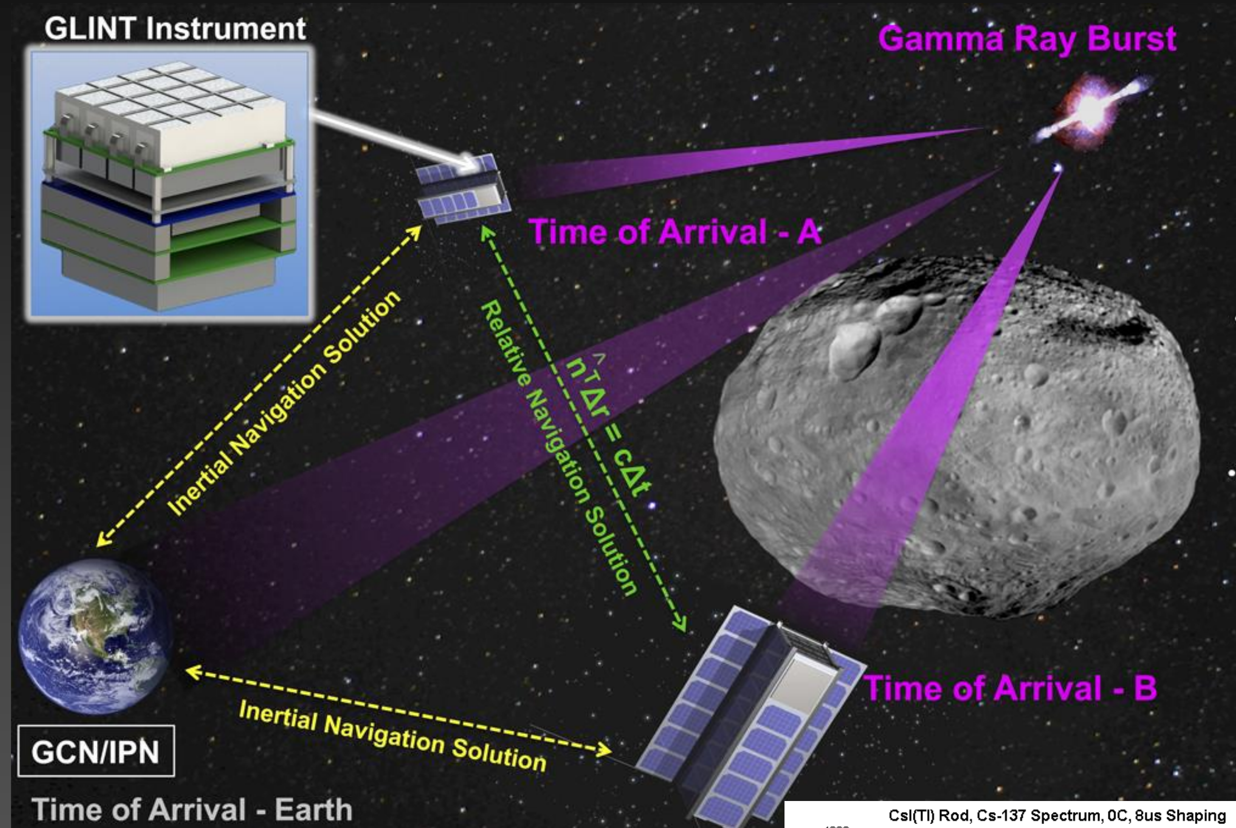
Programmatic Directions and Trends

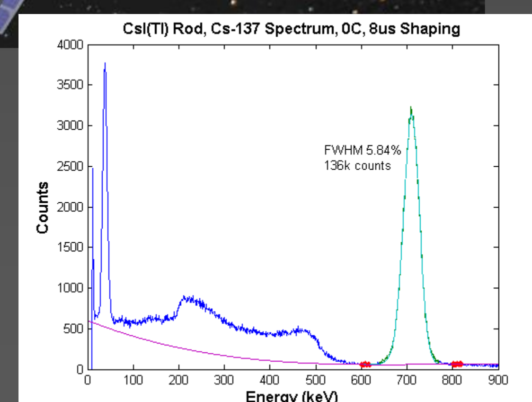
- First practical flight pulsar-based navigation systems *NOT* likely to be simple change-outs (form, fit, function)
  - Cannot simply impose functional equivalence into existing avionics and navigation systems based on GNSS or star trackers
- Likely to be special-purpose systems for specific application needs and niches
- Example niche application:
  - Anticipated loading of DSN system and its replacements
  - Accuracies achievable in outer Solar System
- Also likely that a multi-modal approach blending high energy photons with other technologies may provide best systematic solution
  - Advanced detectors, economies of scale, chipscale components
- Crewed missions require significantly reduced risk
- Next Step:
  - Programmatic vehicle to gather and analyze data and explore all available candidate technologies
    - Compete vs. complement

Future Endeavors

Merge Multiple Energy Bands
- Fold in burst data to pulsar data
- Hybrid detector development

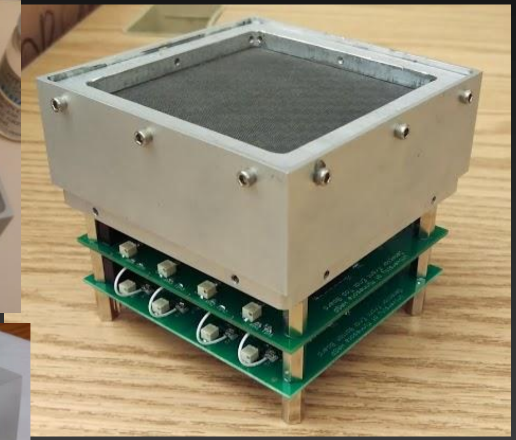
CubeSat Missions
- Good demonstration platforms
- Attractive payload

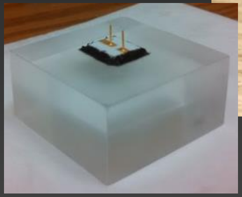


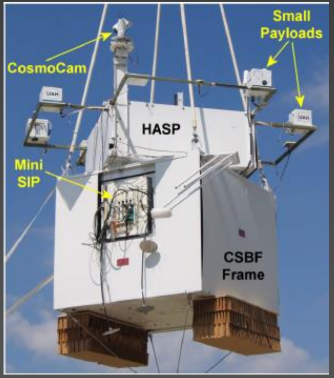


Future Endeavors (cont.)

- Modular X-ray Attitude Instrument
  - Build
  - Test
  - Flights
- Upcoming High-Altitude Student Platform (HASP) Balloon Launches
- Next flight <u>September 2015</u>
- High-Altitude X-Ray Detector Testbed
  - Successful flight 9 August 2014
  - Tested compact X-Ray/Gamma-ray Detector system
  - Two detectors, timing and energy measurements
  - Currently reducing data
  - Three successive flight cycles to date



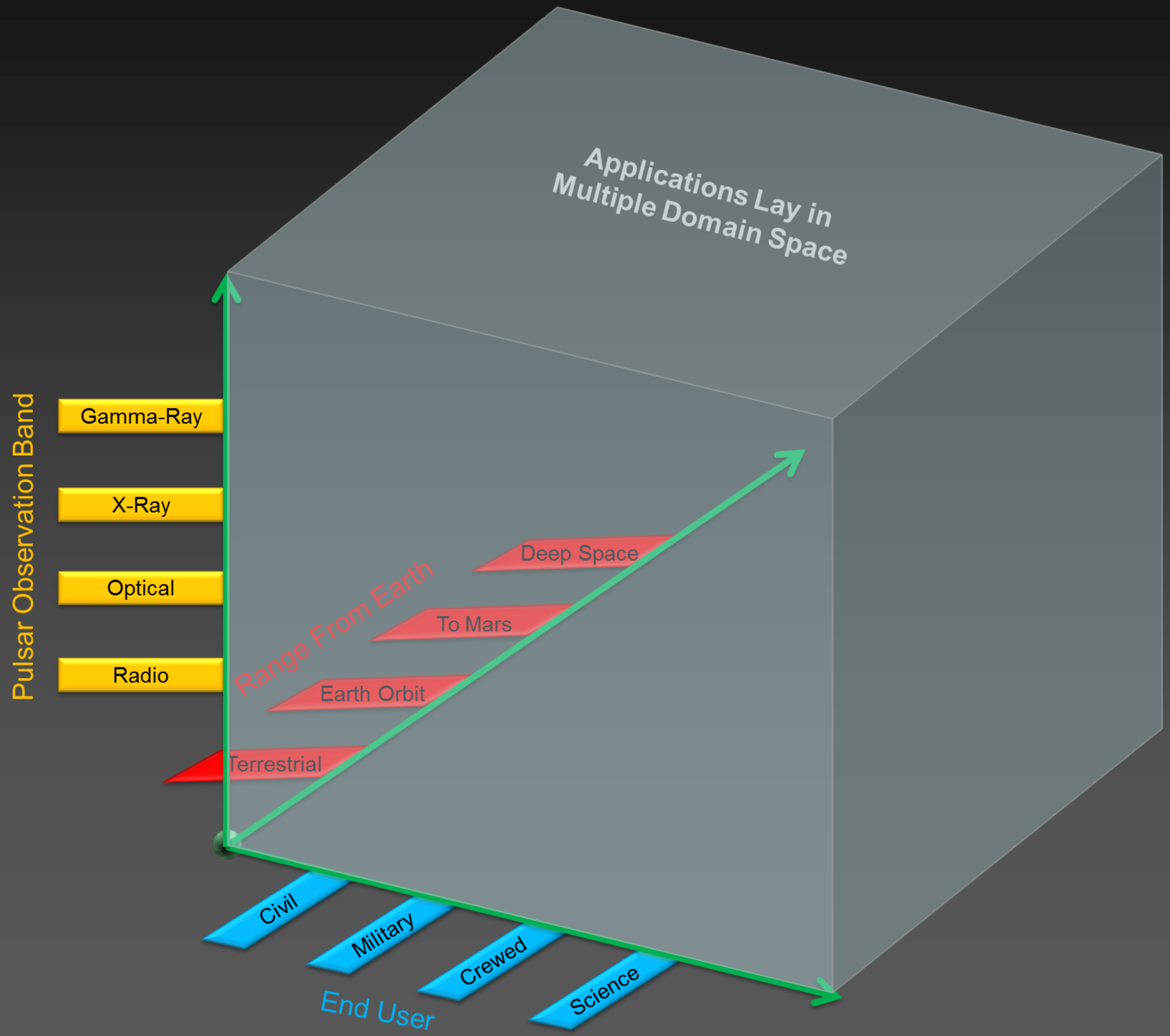




Future Collaborations

- Motivate international partnerships and collaborations between engineering, navigation, and science communities
  - Applications that all communities can support
- Enhanced science return
- Reciprocally, enhanced navigation system designs
- Extend applications nearer to home, to every-day human applications

Applications and Mission Scenarios



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Paul Graven (*Cateni, Inc.*)
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