Deep Space Navigation

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Professional Development Course on Principles of Astrodynamics and Mission Design

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Summary

- Introduction
- Navigation measurements
- Flight path estimation
- Flight path control
- Navigation accuracies
- Navigation characteristics of selected missions (separate presentation by Bobby G. Williams)
- Future navigation challenges
- Future evolution of navigation capabilities

Navigation Tasks

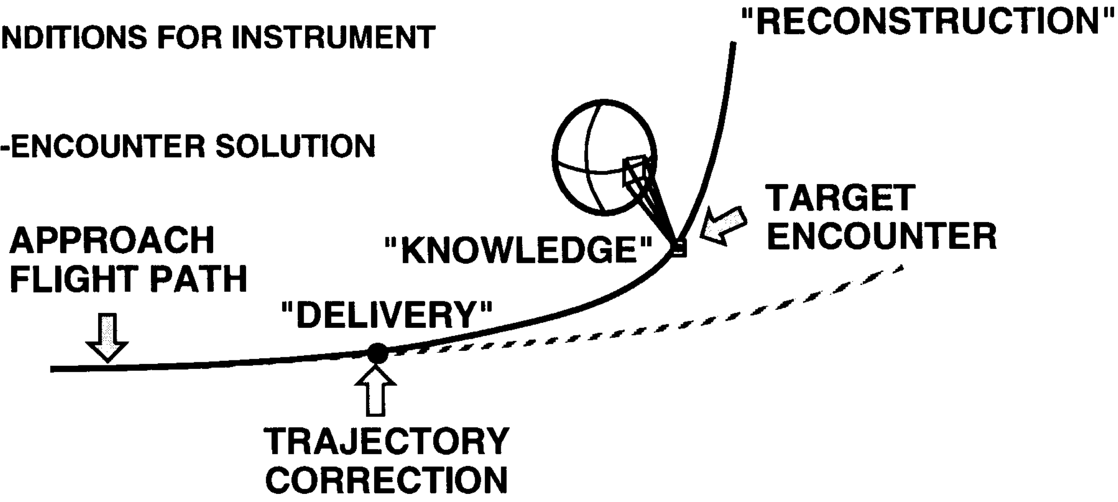
- **These five tasks need to be performed for successful navigation, be it on Earth or in interplanetary space:**

Task	Example on Earth (Hiking)	Example in Space
(1) Obtain a Map	Obtain road map, digital map database	Develop planetary ephemerides
(2) Develop a Travel Plan	Select trail(s) to reach destination, estimate arrival time	Select orbit(s) to reach destination planet/asteroid, calculate arrival time
(3) Take Meaningful Measurements	Note time arrived at significant landmarks, note direction with a compass	Use radio signals and/or optical measurements to compute spacecraft position and velocity.
(4) Calculate One's Position	Compare actual arrival time at waypoint to predicted time	Estimate size, shape and orientation of orbit
(5) Select a New Optimal Route	Walk faster/slower, change direction	Change orbit using propulsion system

- **Tasks 1-2 are done pre-launch; others from launch to end of mission**

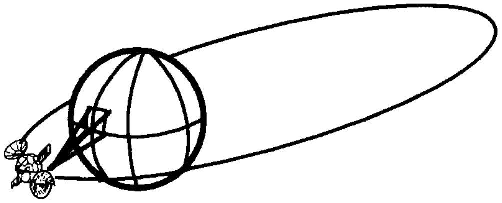
Navigation Objectives in Different Mission Phases

- **FLYBY/ORBIT INSERTION:**
  - DELIVER SPACECRAFT TO DESIRED LOCATION AT DESIRED TIME
  - PREDICT ENCOUNTER CONDITIONS FOR INSTRUMENT POINTING/SEQUENCING
  - OBTAIN ACCURATE POST-ENCOUNTER SOLUTION

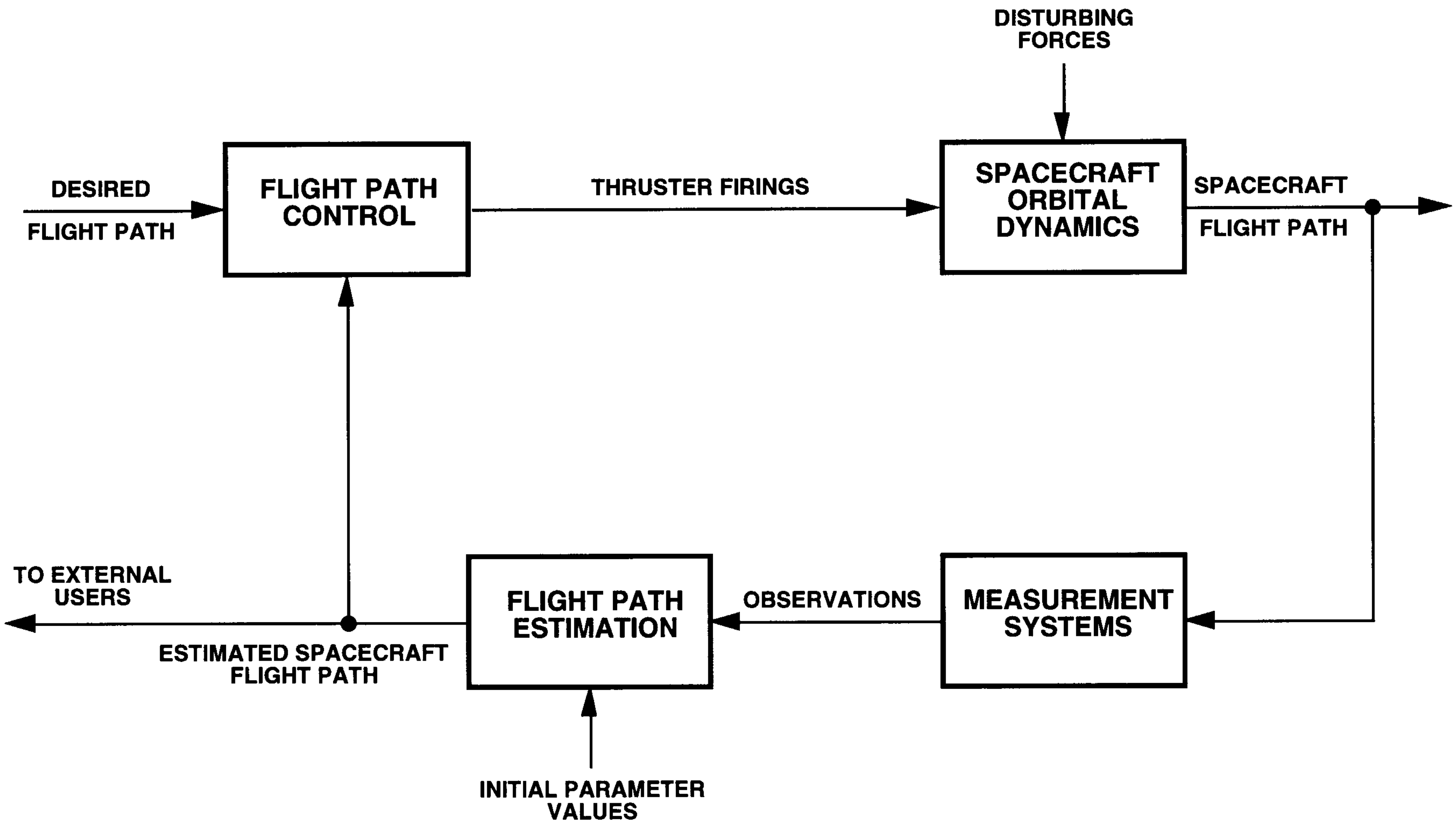


STEPS: MEASUREMENT ACQUISITION, ORBIT DETERMINATION, MANEUVER COMPUTATION AND COMMAND

- **ORBITER:**
  - DETERMINE TRAJECTORY ON CONTINUING BASIS
  - MAINTAIN DESIRED ORBIT



Deep Space Navigation System Block Diagram

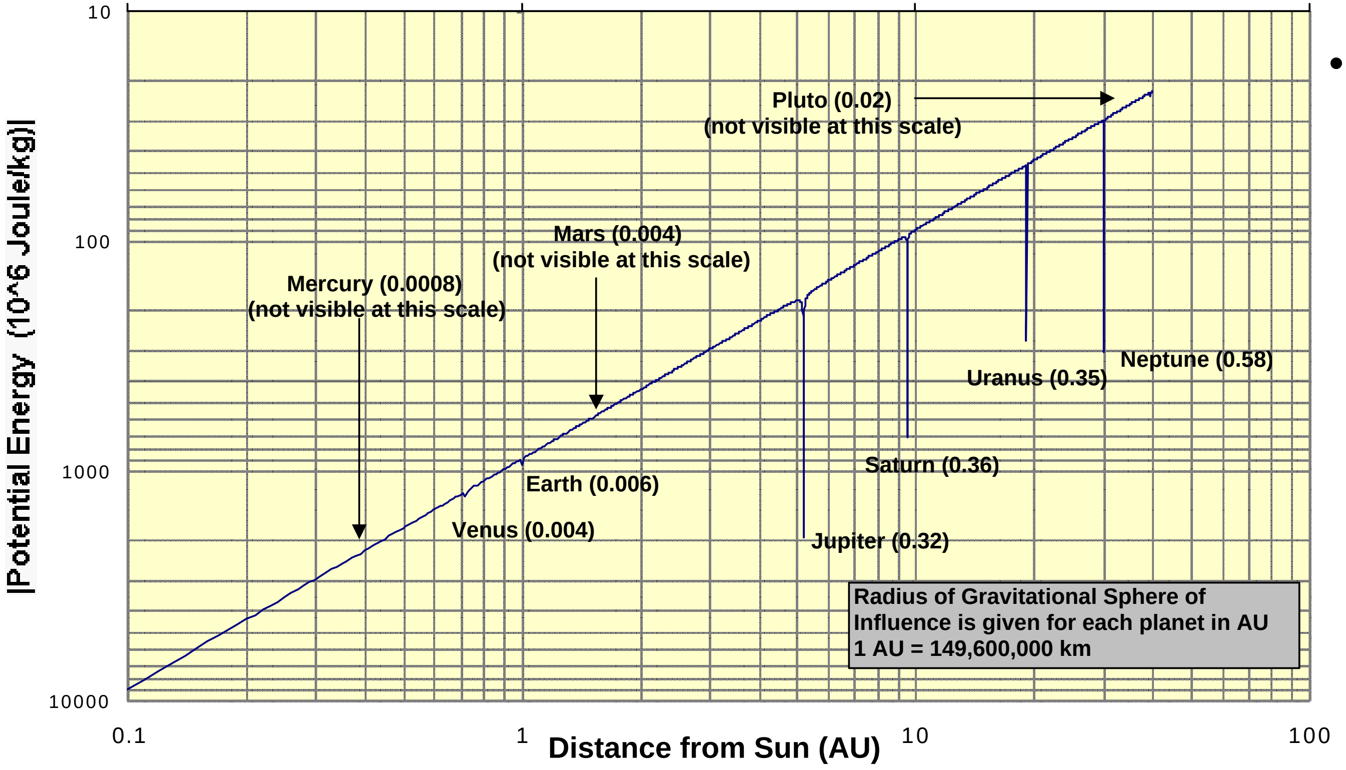


Spacecraft Orbital Dynamics

- **Translational motion of spacecraft is determined by number of forces that act on spacecraft:**
  - **Gravitational forces**
    - **Dominant body force (dominant body is treated as spherically symmetric; this produces pure Keplerian motion)**
    - **Non-dominant body forces**
    - **Dominant body gravity field asymmetries**
    - **General relativistic effects**
  - **Nongravitational forces**
    - **Thruster firings**
      - **Trajectory control**
      - **Attitude control**
    - **Gas leaks**
    - **Solar radiation pressure**
    - **Aerodynamic drag**

Gravitational Influence of Sun and Planets

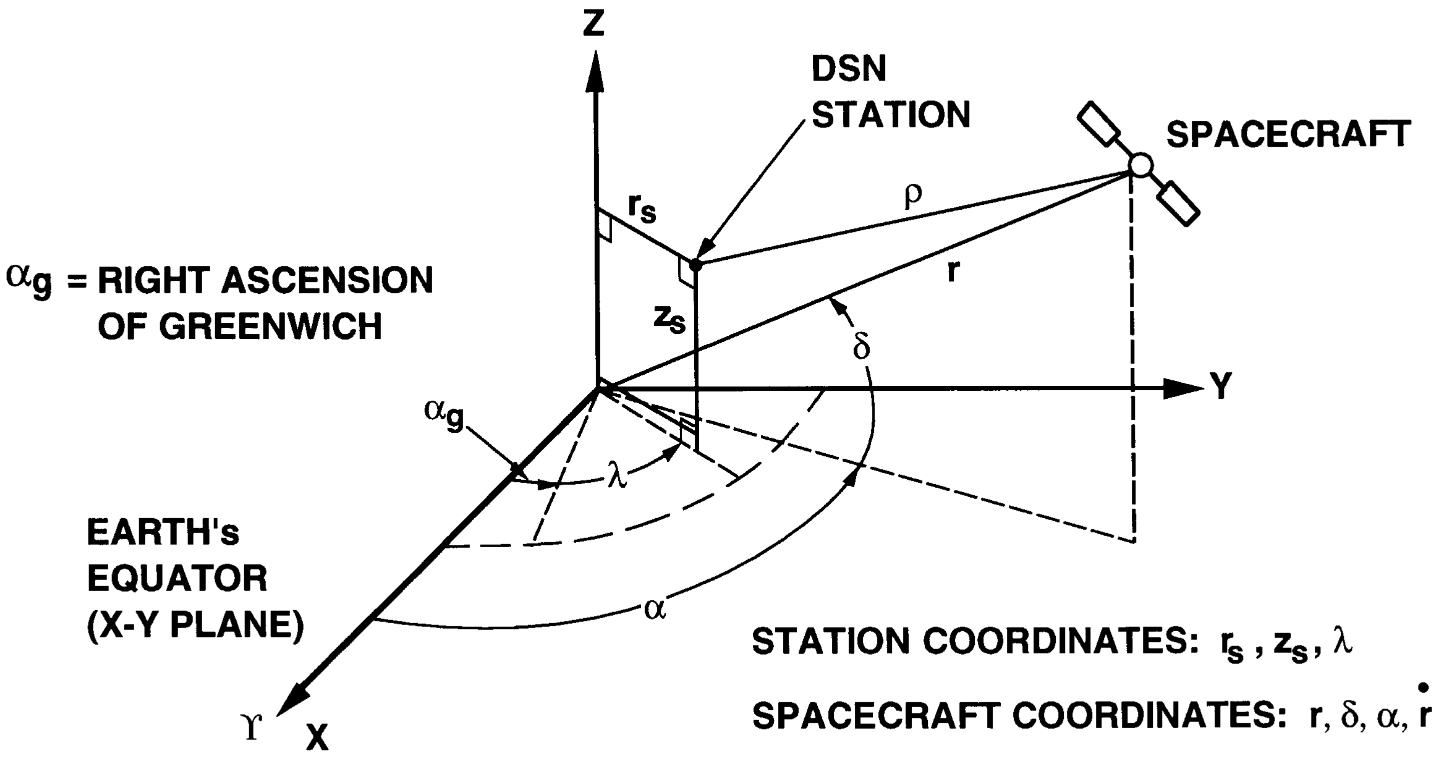
- **In interplanetary space, gravitational effect of Sun is dominant**
- **Gravitational perturbations due to planets are not noticeable until spacecraft is significantly closer to planet than to Sun**



Radius of Gravitational Sphere of Influence is given for each planet in AU
1 AU = 149,600,000 km

- **This impacts navigation planning in two ways:**
  - **Interplanetary trajectory planning can begin with two-body approximations with Sun as dominant body**
  - **Gravitational influence of target planet has only very late influence on spacecraft trajectory; planet's presence is not noticed until spacecraft is practically there**

Basic Elements of Spacecraft Trajectory Information



STATION COORDINATES: r_s , z_s , λ

SPACECRAFT COORDINATES: $r, \delta, \alpha, \dot{r}, \dot{\delta}, \dot{\alpha}$

GEOCENTRIC SPACECRAFT COORDINATE DEFINITIONS:

r = RANGE

$\dot{r}$ = RANGE-RATE

δ = DECLINATION

$\dot{\delta}$ = DECLINATION RATE

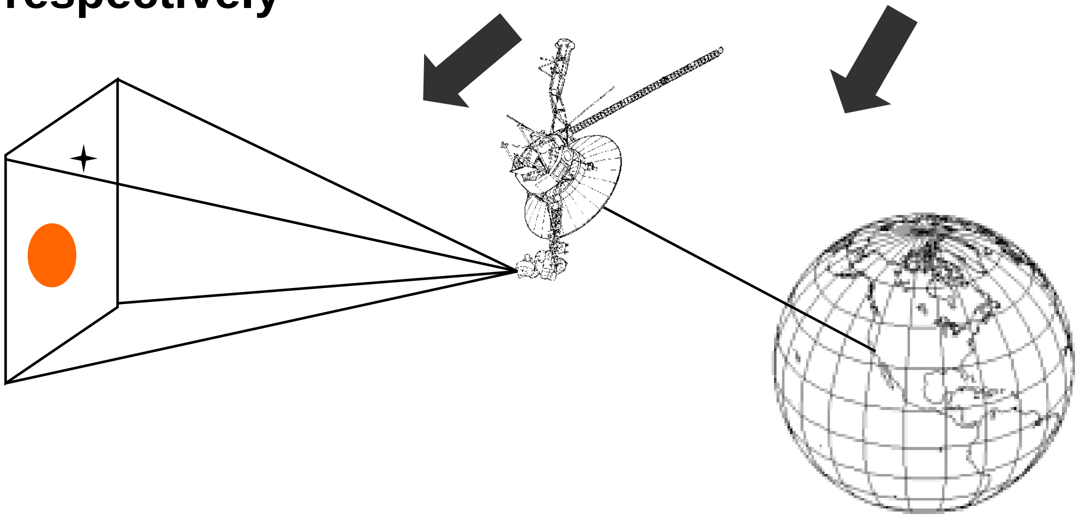
α = RIGHT ASCENSION

$\dot{\alpha}$ = RIGHT ASCENSION RATE

- **SPACECRAFT TRAJECTORY IS DESCRIBED BY 6-PARAMETER STATE VECTOR OF POSITION AND VELOCITY COMPONENTS**

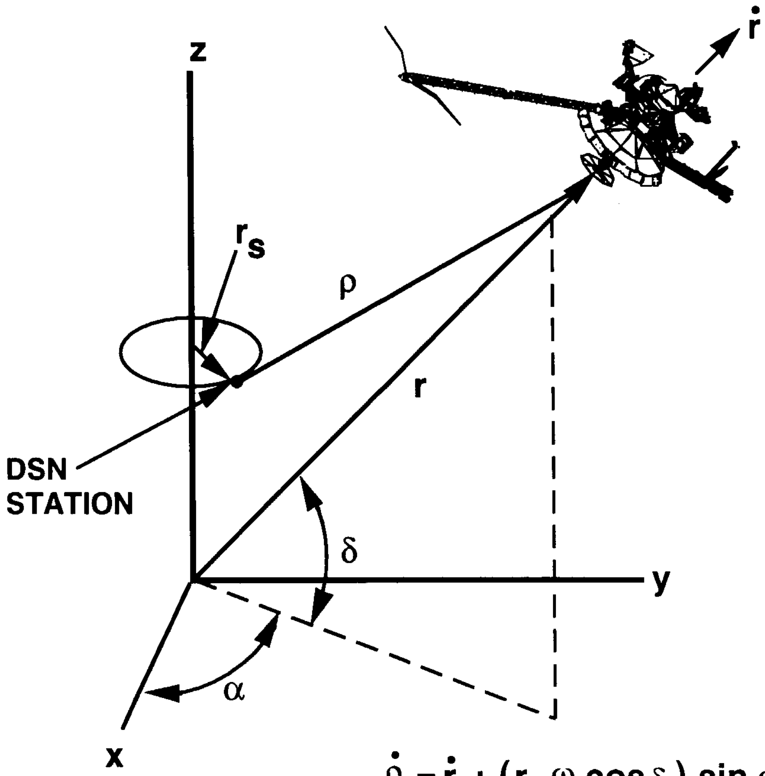
Navigation Measurements -- Overview

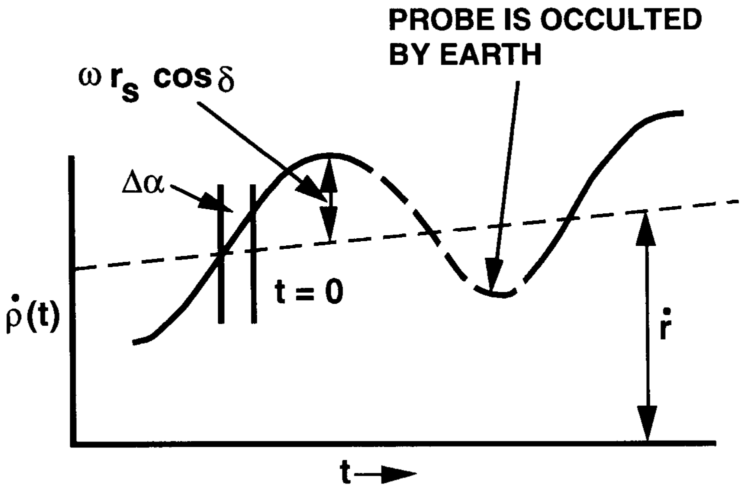
- **Various measurement systems are used to infer position and velocity of spacecraft**
- **Measurements are related to position and velocity, but typically only measure fraction of total set of position and velocity components and are corrupted by random and systematic errors**
- **Measurements are derived from on-board camera or from telecommunication link between spacecraft and Earth**
- **These measurements are referred to as optical and radio metric measurements, respectively**



Range and Doppler Tracking

- TWO-WAY RANGE AND DOPPLER DIRECTLY MEASURE LINE-OF-SIGHT COMPONENTS OF SPACECRAFT STATE
- DIURNAL SIGNATURE OF EARTH ROTATION ALSO PROVIDES ANGULAR STATE INFORMATION





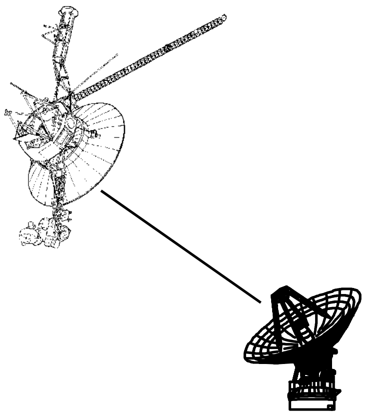
$\dot{\rho} = \dot{r} + (r_s \omega \cos\delta) \sin \omega (t - t_m)$ + OBSERVATION ERROR

WHERE t_m IS THE TIME OF MERIDIAN CROSSING

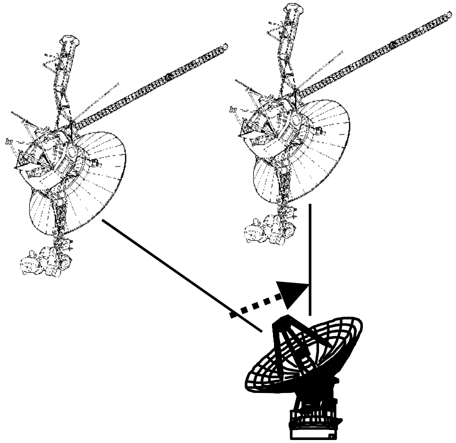
Characteristics of Single-Station Doppler and Range Orbit Determination Capabilities

- **Radial velocity derived from mean trend in Doppler data**
- **Radial position derived from mean trend in range data (or inferred from processing of Doppler data)**
- **Declination derived principally from amplitude of 24-hour signature in Doppler or range data -- poorly determined near zero declination**
- **Right ascension derived principally from phase of 24-hour signature in Doppler or range data**
- **Very accurate modeling of measurements and spacecraft dynamics is needed to infer quantities not measured directly -- angular position and rate components**

Radio Metric Measurements -- Radial Data Types

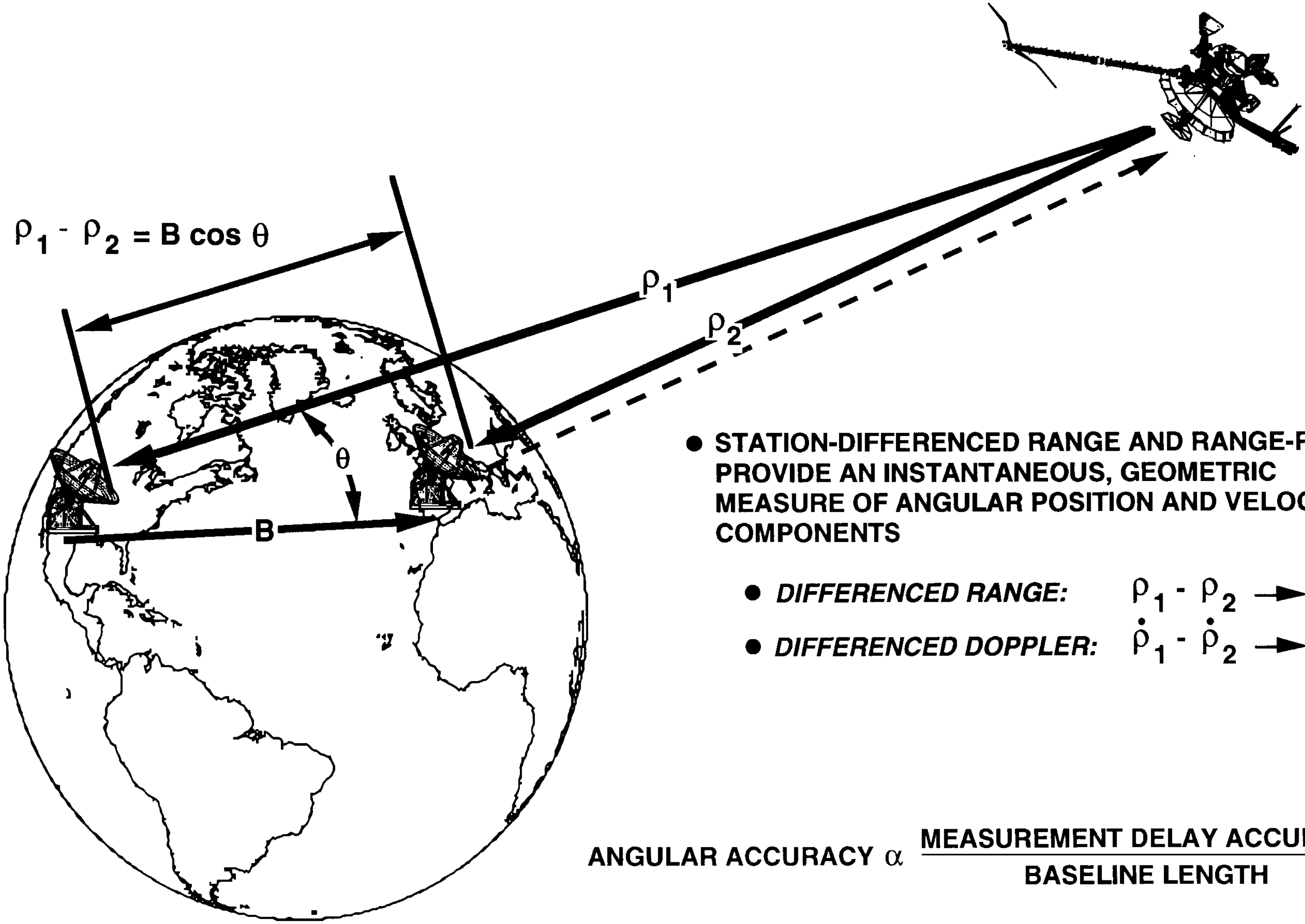


- Doppler
  - Measurements are comparisons of transmitted frequency (from ground station or spacecraft) with received frequency on ground; typical frequencies are at S-band (2 GHz) and X-band (7-8 GHz)
  - Useful for all mission phases
  - Highly reliable; used in all interplanetary missions to date
- Range
  - Measurements are typically two-way light time for radio signal to propagate between ground stations and spacecraft; typical frequencies are also at S- and X-band
  - Most useful during interplanetary cruise, planetary approach, and for surface positioning
  - Used in nearly all interplanetary missions since late 1960s



- Near Simultaneous Tracking
  - Two-way ranging between ground station and spacecraft, followed by additional ranging to second spacecraft in nearby part of sky in quick succession
  - Used to infer angular information if error sources are well-modeled; useful if one spacecraft is planetary orbiter and second is nearing that planet
  - Used between (1) Mars Pathfinder and MGS, (2) MGS and MCO, (3) MGS and MPL

Angular Tracking Using Station-Differenced Observables

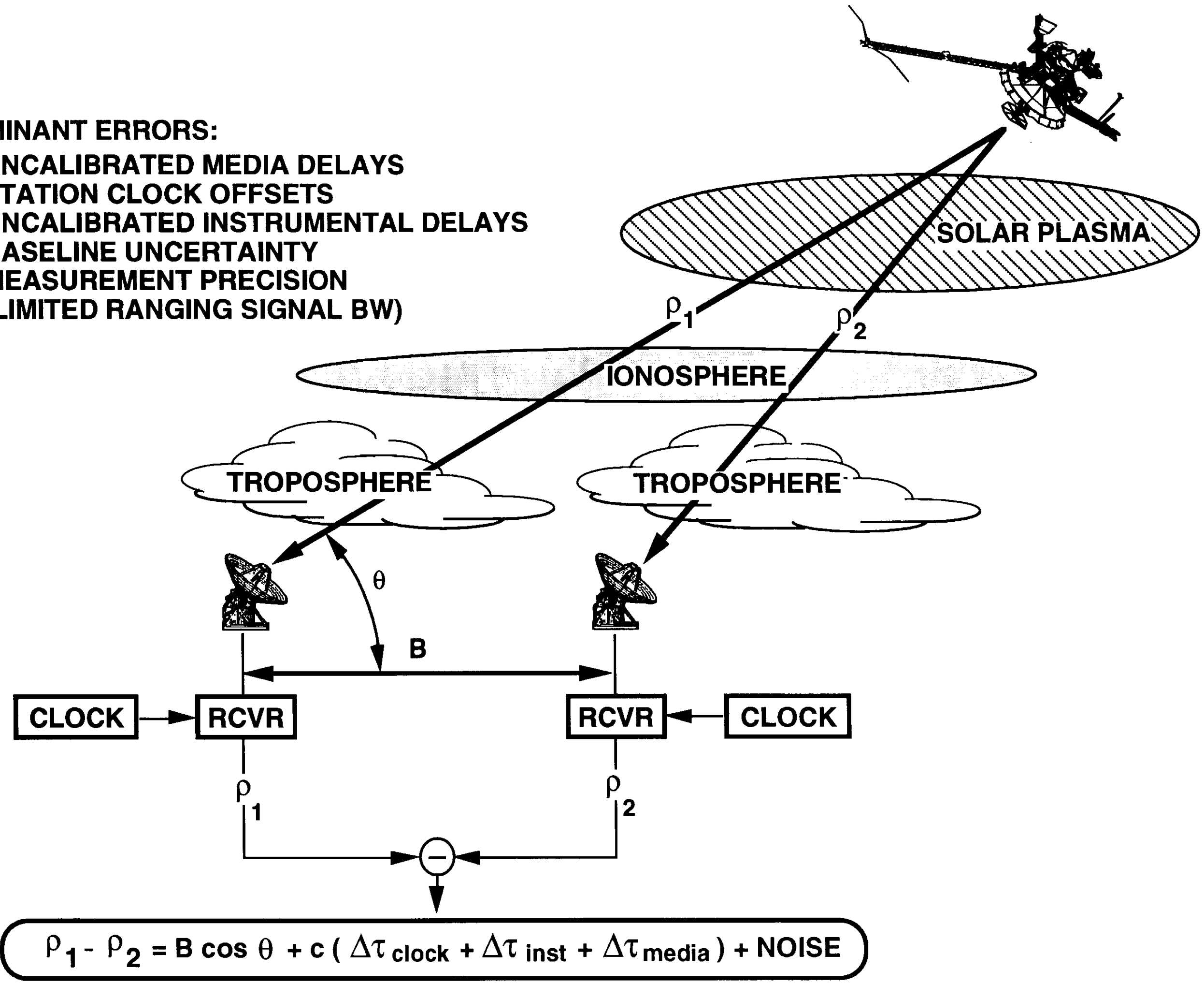


- **STATION-DIFFERENCED RANGE AND RANGE-RATE PROVIDE AN INSTANTANEOUS, GEOMETRIC MEASURE OF ANGULAR POSITION AND VELOCITY COMPONENTS**
  - ***DIFFERENCED RANGE:*** $\rho_1 - \rho_2 \rightarrow \theta$
  - ***DIFFERENCED DOPPLER:*** $\dot{\rho}_1 - \dot{\rho}_2 \rightarrow \dot{\theta}$

$$\text{ANGULAR ACCURACY } \alpha \ \frac{\text{MEASUREMENT DELAY ACCURACY}}{\text{BASELINE LENGTH}}$$

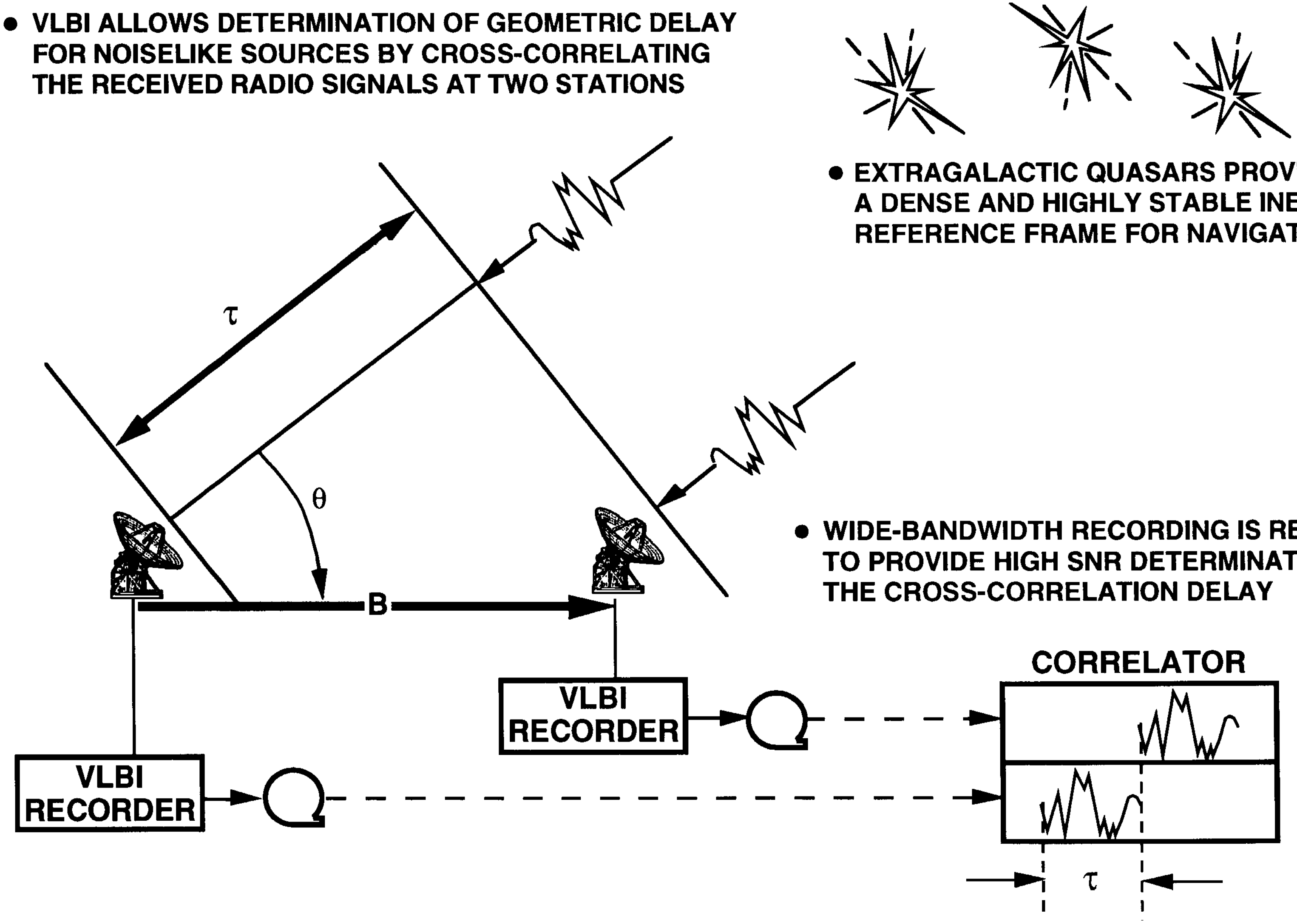
Differenced-Range Measurement Errors

- **DOMINANT ERRORS:**
  - **UNCALIBRATED MEDIA DELAYS**
  - **STATION CLOCK OFFSETS**
  - **UNCALIBRATED INSTRUMENTAL DELAYS**
  - **BASELINE UNCERTAINTY**
  - **MEASUREMENT PRECISION (LIMITED RANGING SIGNAL BW)**



$$\rho_1 - \rho_2 = \mathbf{B} \cos\theta + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + \text{NOISE}$$

Very Long Baseline Interferometry

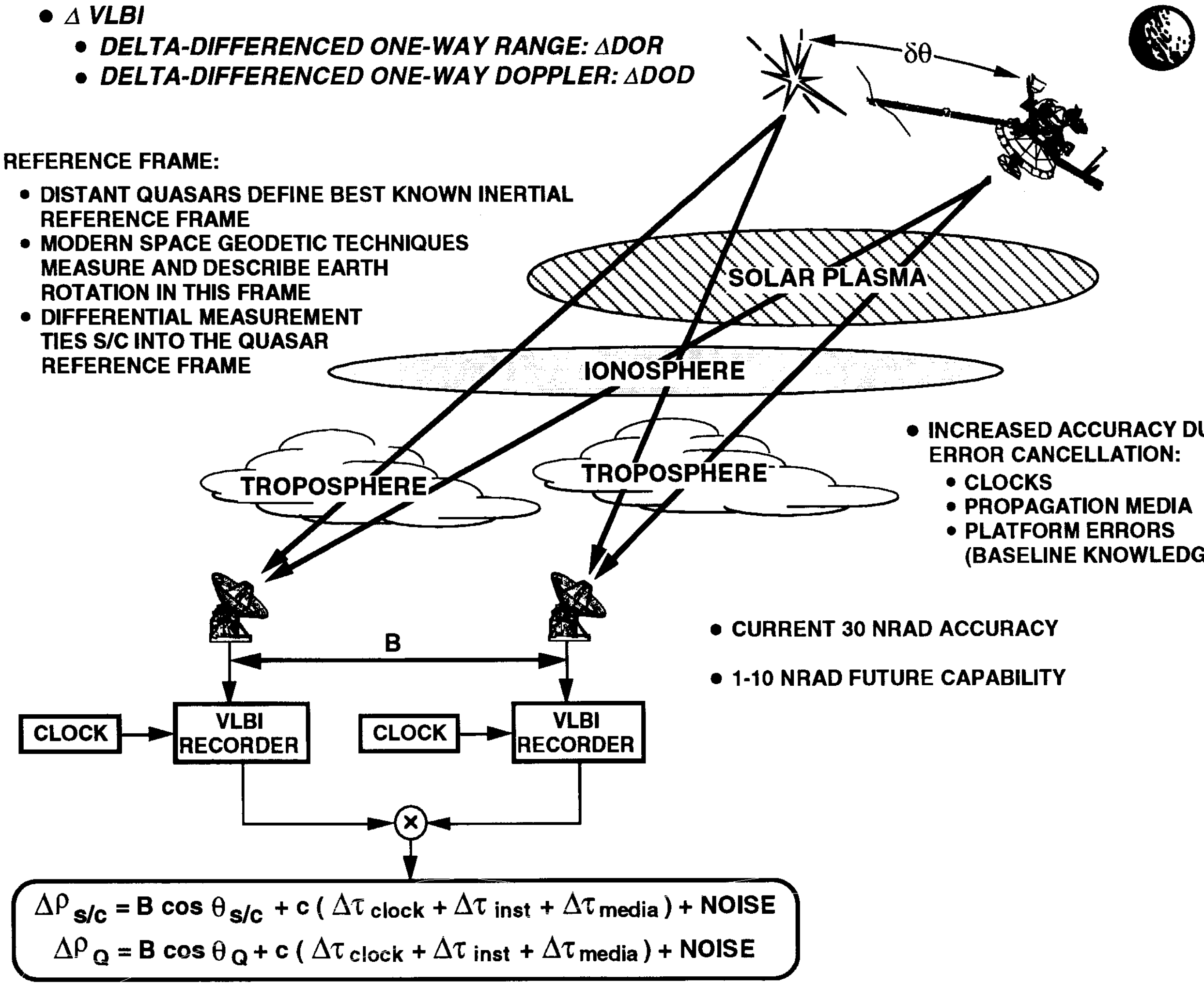


- **VLBI ALLOWS DETERMINATION OF GEOMETRIC DELAY FOR NOISELIKE SOURCES BY CROSS-CORRELATING THE RECEIVED RADIO SIGNALS AT TWO STATIONS**
- **EXTRAGALACTIC QUASARS PROVIDE A DENSE AND HIGHLY STABLE INERTIAL REFERENCE FRAME FOR NAVIGATION**
- **WIDE-BANDWIDTH RECORDING IS REQUIRED TO PROVIDE HIGH SNR DETERMINATION OF THE CROSS-CORRELATION DELAY**

Spacecraft-Quasar Differential Angular Techniques

- *Δ VLBI*
  - ***DELTA-DIFFERENCED ONE-WAY RANGE: ΔDOR***
  - ***DELTA-DIFFERENCED ONE-WAY DOPPLER: ΔDOD***

- **REFERENCE FRAME:**
  - **DISTANT QUASARS DEFINE BEST KNOWN INERTIAL REFERENCE FRAME**
  - **MODERN SPACE GEODETIC TECHNIQUES MEASURE AND DESCRIBE EARTH ROTATION IN THIS FRAME**
  - **DIFFERENTIAL MEASUREMENT TIES S/C INTO THE QUASAR REFERENCE FRAME**



- **INCREASED ACCURACY DUE TO ERROR CANCELLATION:**
  - **CLOCKS**
  - **PROPAGATION MEDIA**
  - **PLATFORM ERRORS (BASELINE KNOWLEDGE)**

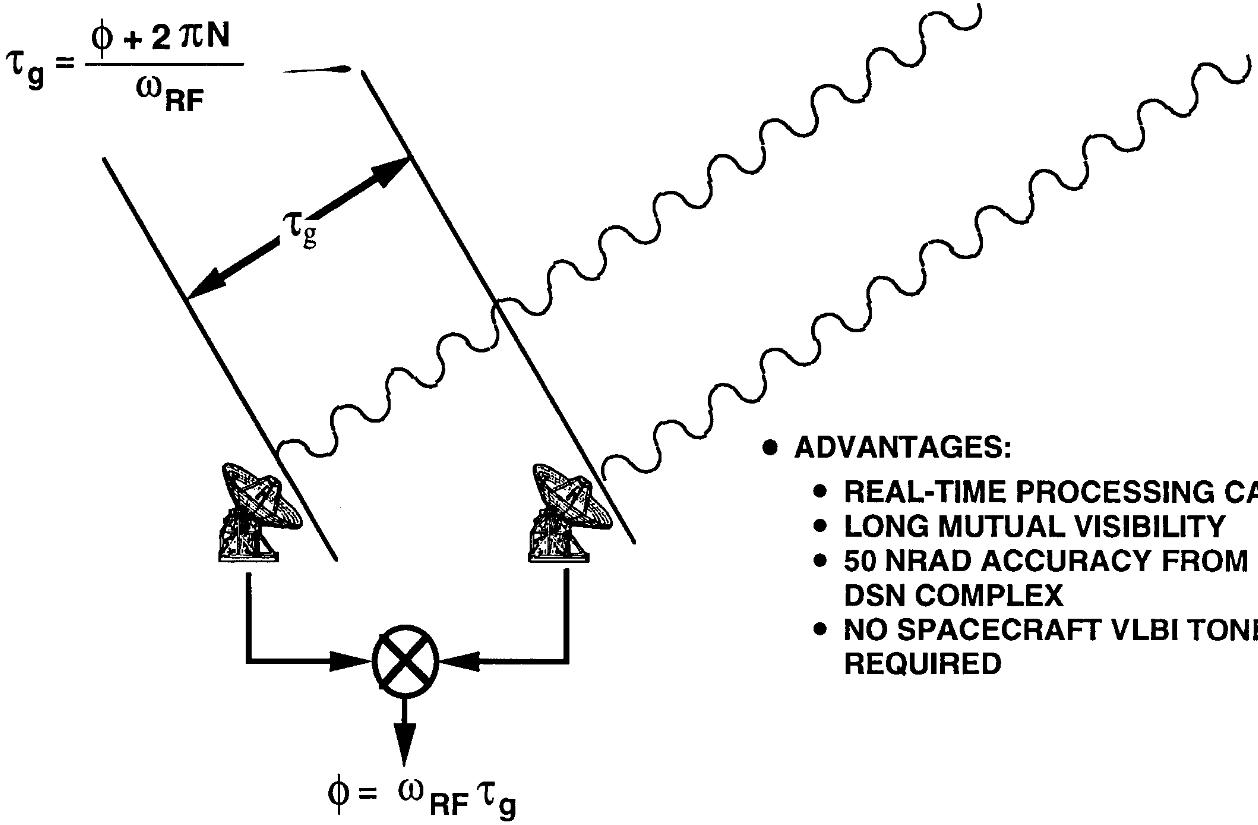
- **CURRENT 30 NRAD ACCURACY**
- **1-10 NRAD FUTURE CAPABILITY**

$$\Delta\rho_{s/c} = B\cos\theta_{s/c} + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + NOISE$$

$$\Delta\rho_{Q} = B\cos\theta_{Q} + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + NOISE$$

Connected Element Interferometry

- ***CONNECTED ELEMENT INTERFEROMETRY (CEI):***
  - **ON SHORT BASELINES, THE INTERFEROMETRIC PHASE OBSERVABLE CAN BE USED DIRECTLY TO OBTAIN AN EXTREMELY PRECISE MEASURE OF GEOMETRIC DELAY**



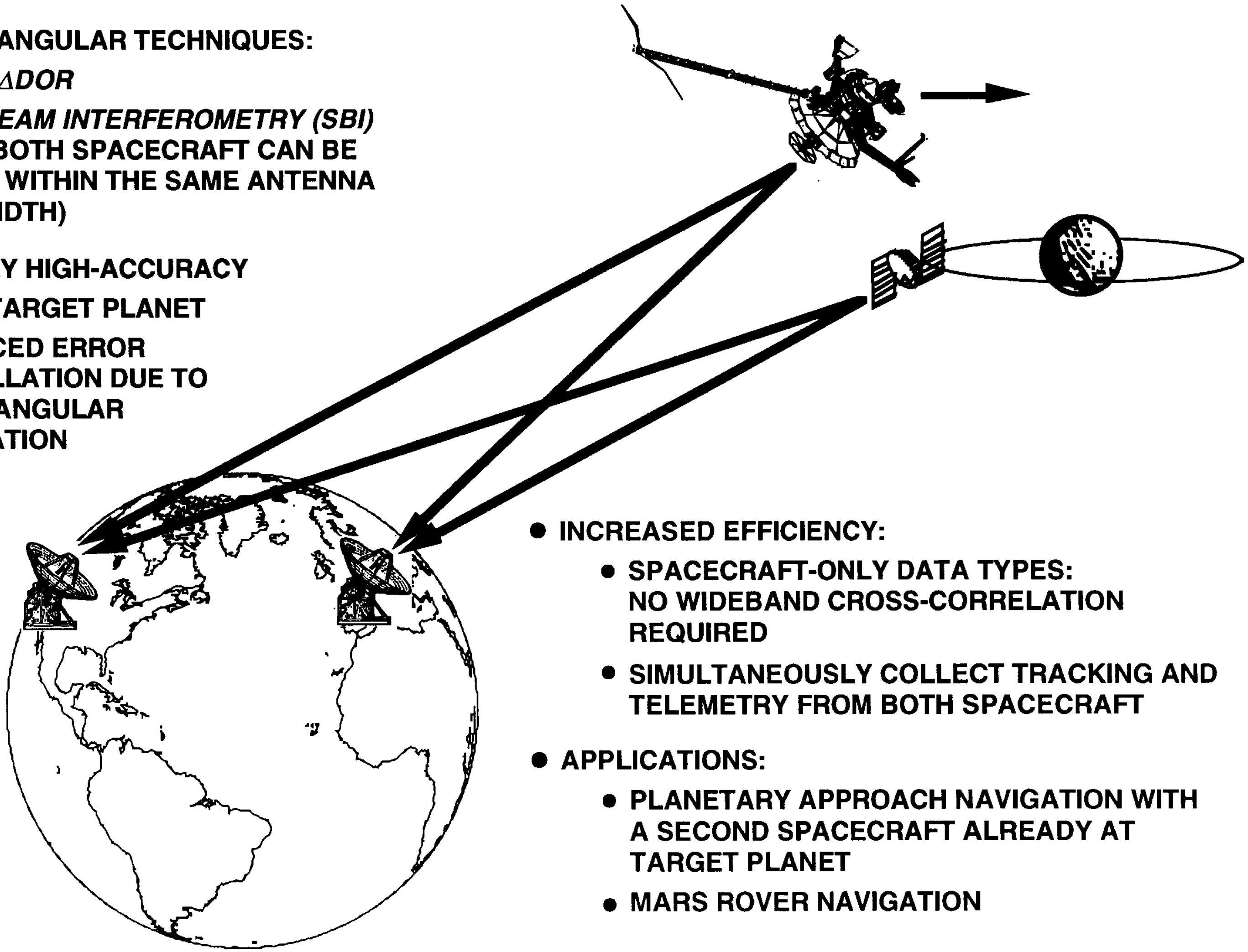
$$\tau_g = \frac{\phi + 2\pi N}{\omega_{RF}}$$

$$\phi = \omega_{RF}\,\tau_g$$

- **ADVANTAGES:**
  - **REAL-TIME PROCESSING CAPABILITY**
  - **LONG MUTUAL VISIBILITY**
  - **50 NRAD ACCURACY FROM A SINGLE DSN COMPLEX**
  - **NO SPACECRAFT VLBI TONES REQUIRED**

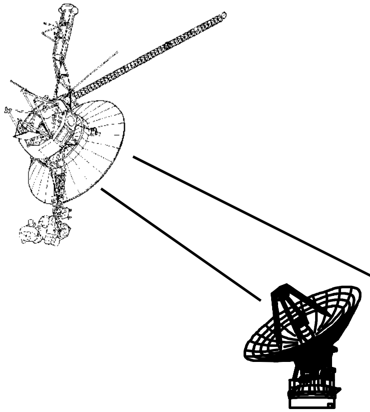
Multiple-Spacecraft Doubly-Differenced Angular Techniques

- **MULTI-S/C ANGULAR TECHNIQUES:**
  - ***S/C-S/C ΔDOR***
  - ***SAME BEAM INTERFEROMETRY (SBI)*** **(WHEN BOTH SPACECRAFT CAN BE VIEWED WITHIN THE SAME ANTENNA BEAMWIDTH)**
- **EXTREMELY HIGH-ACCURACY**
  - **TIE TO TARGET PLANET**
  - **ENHANCED ERROR CANCELLATION DUE TO SMALL ANGULAR SEPARATION**

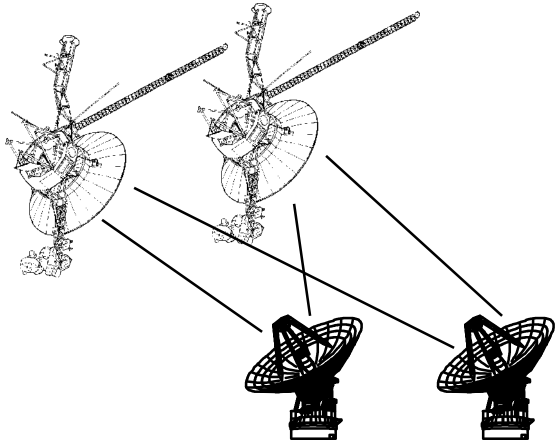


- **INCREASED EFFICIENCY:**
  - **SPACECRAFT-ONLY DATA TYPES: NO WIDEBAND CROSS-CORRELATION REQUIRED**
  - **SIMULTANEOUSLY COLLECT TRACKING AND TELEMETRY FROM BOTH SPACECRAFT**
- **APPLICATIONS:**
  - **PLANETARY APPROACH NAVIGATION WITH A SECOND SPACECRAFT ALREADY AT TARGET PLANET**
  - **MARS ROVER NAVIGATION**

Radio Metric Measurements -- Quasi-Interferometric Data Types (Spacecraft Signals Only)

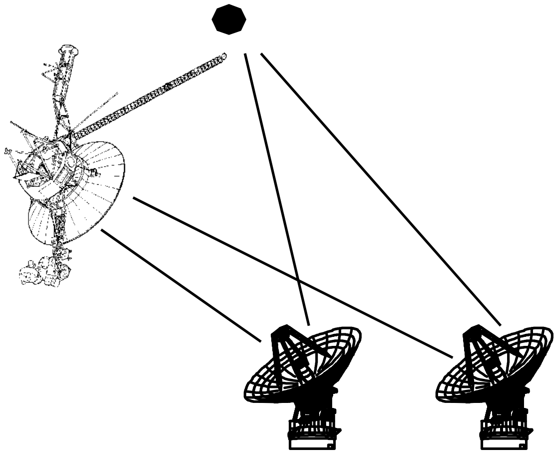


- Differenced Doppler
  - Measurements are difference in Doppler measurements at two different stations
  - Most useful during planetary approach and for planetary orbiters
  - Used in Magellan and Galileo missions
- Differenced Range
  - Measurements are difference in arrival times of spacecraft downlink signal at two different stations
  - Most useful during planetary approach and for outer planet orbiters
  - Used in Voyager mission

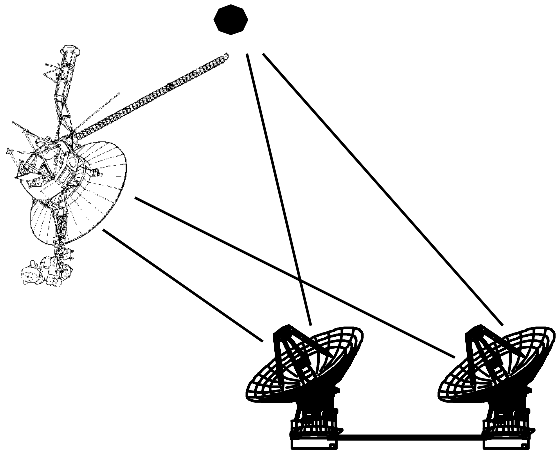


- Spacecraft-Spacecraft ∆DOR
  - “Differenced” differenced range, using signal cross-correlation to obtain group delay of signals arriving at two stations
  - Used to obtain angular information; useful if one spacecraft is planetary orbiter and second is nearing that planet
  - Applications are planetary approach navigation and planetary rover navigation

Radio Metric Measurements -- Interferometric Data Types

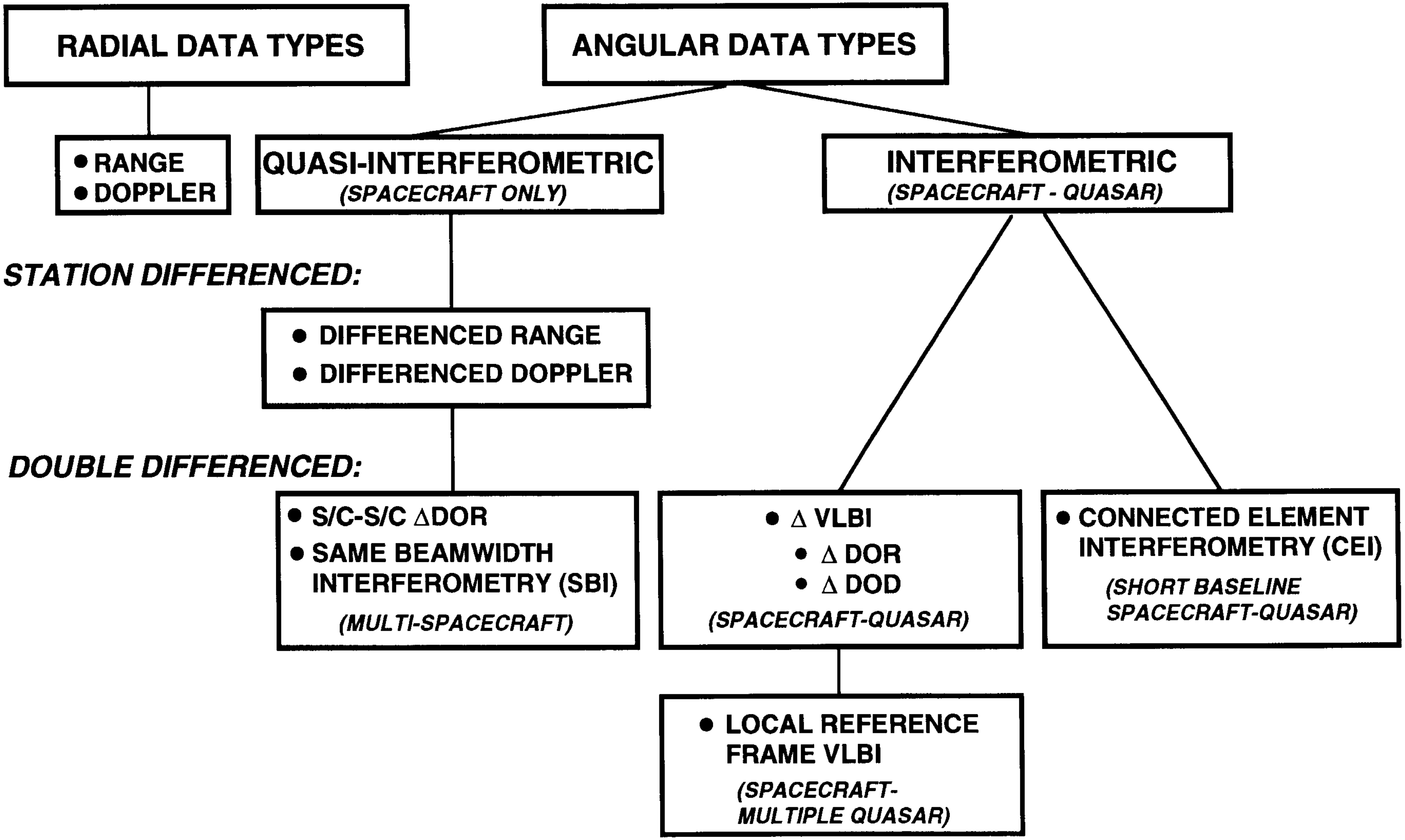


- Spacecraft-Quasar ΔDOR
  - Similar to Spacecraft-Spacecraft ΔDOR, with second spacecraft signal replaced with natural radio source such as quasar
  - Useful for planetary approach if no other spacecraft are nearby in sky
  - Used on Voyager, Ulysses, Magellan, Mars Observer, and Galileo



- Connected Element Interferometry
  - Uses doubly-differenced phase delay observable instead of group delay observable
  - Correlation can be performed in real-time
  - Applications are planetary approach navigation and interplanetary cruise navigation

Earth-Based Radio Tracking Family Tree



RADIAL DATA TYPES

- RANGE
- DOPPLER

ANGULAR DATA TYPES

QUASI-INTERFEROMETRIC
(SPACECRAFT ONLY)

STATION DIFFERENCED:

- DIFFERENCED RANGE
- DIFFERENCED DOPPLER

DOUBLE DIFFERENCED:

- S/C-S/C ΔDOR
- SAME BEAMWIDTH INTERFEROMETRY (SBI)

(MULTI-SPACECRAFT)

INTERFEROMETRIC
(SPACECRAFT - QUASAR)

- Δ VLBI
  - Δ DOR
  - Δ DOD

(SPACECRAFT-QUASAR)

- LOCAL REFERENCE FRAME VLBI

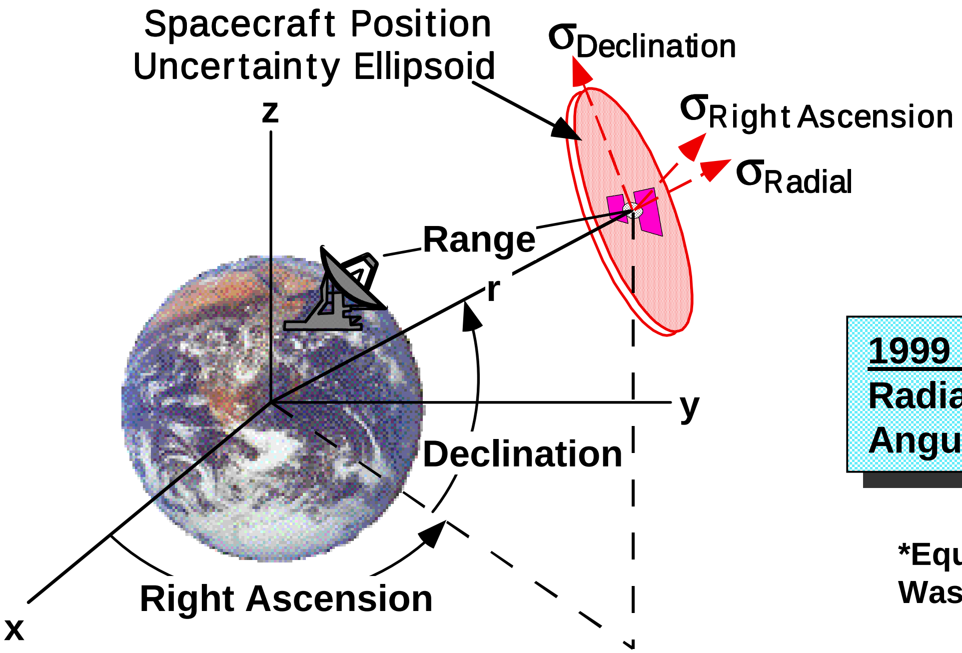
(SPACECRAFT-MULTIPLE QUASAR)

- CONNECTED ELEMENT INTERFEROMETRY (CEI)

(SHORT BASELINE SPACECRAFT-QUASAR)

Radio Metric Orbit Determination Accuracy -- Radial Versus Angular Components

- **For most interplanetary missions, spacecraft position uncertainty is much smaller in Earth-spacecraft ("radial") direction than in any angular ("plane-of-sky") direction**
  - **Radial components of position and velocity are directly measured by range and Doppler observations**
  - **In absence of other data, angular components are much more difficult to determine -- they require either changes in geometry between observer and spacecraft or additional simultaneous observer, neither of which is logistically simple to accomplish**
  - **Angular errors are more than 1000 x radial errors even under the most favorable conditions (see below) when depending on range and Doppler measurements**



However: ΔDOR and NST data can directly measure these otherwise weaker angular components with varying accuracies

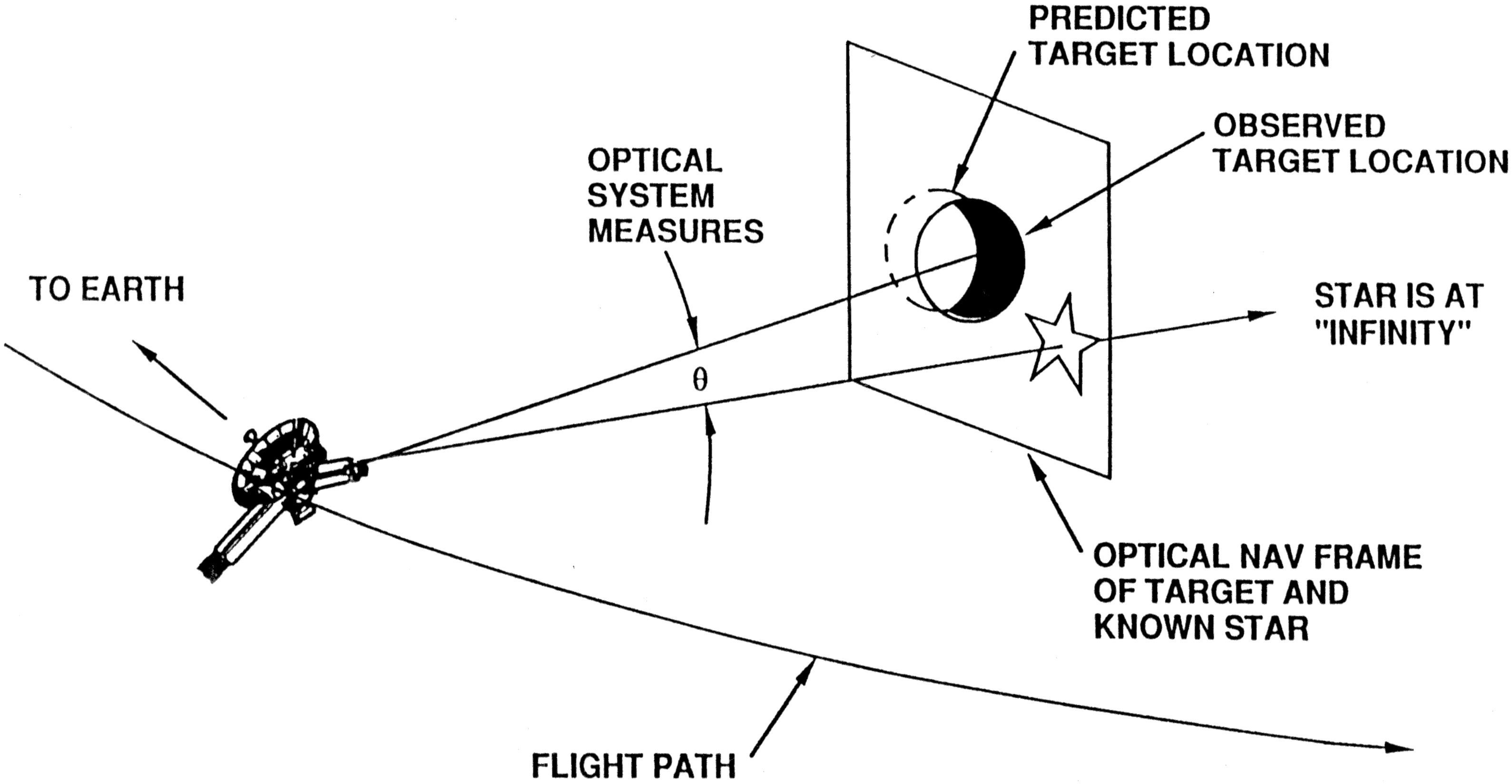
1999 Capability	Position	Velocity
Radial Error	2 m	0.1 mm/s
Angular Error (at 1 AU)	3 km*	0.1 m/s

***Equivalent to angle subtended by quarter atop Washington Monument as viewed from Chicago**

Radio Metric Orbit Determination for Planetary Orbiter

- Doppler tracking of spacecraft in orbit about another planet does not determine all orbital elements equally well
  - Longitude of ascending node in plane-of-sky coordinate system difficult to determine
  - Inclination in plane-of-sky coordinate system difficult to determine when near 90°
  - All elements except inclination difficult to determine when plane-of-sky inclination near 0° or 180°
  - Number of poor geometries and degree of severity increase as orbit eccentricity approaches zero
- Multi-station differenced-Doppler data (or functional equivalent) can be used to measure one or more plane-of-sky velocity components and resolve indeterminacies associated with single-station Doppler data

Navigation Measurements -- Optical Data

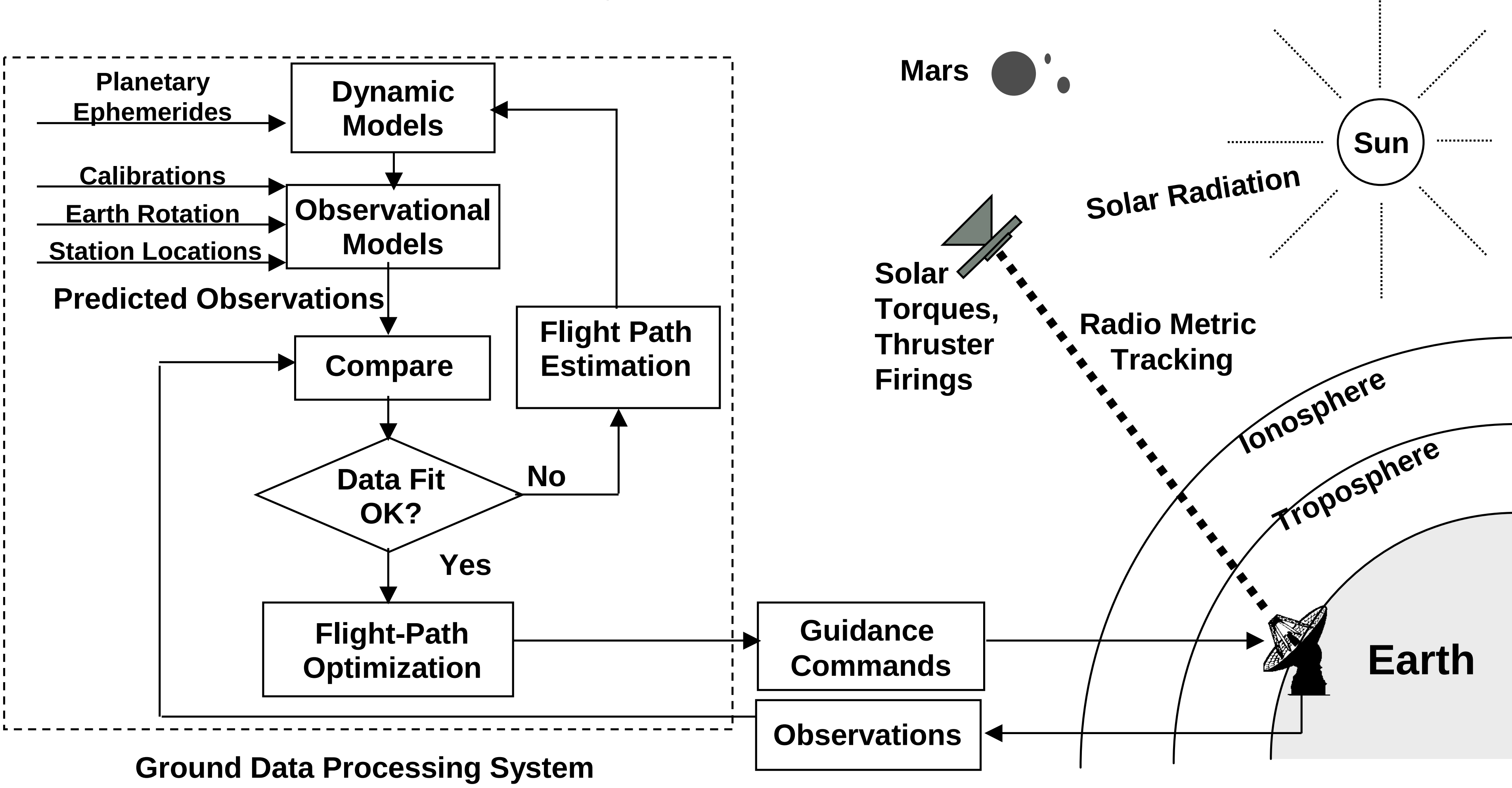


Characteristics of Optical Navigation

- **On-board optical system takes pictures of reference bodies with respect to stars with known celestial locations**
- **These images are then used to compute angular positions of spacecraft with respect to reference bodies**
- **Objective diameter of imaging system limits resolution, due to diffraction; typical angular accuracy is 5 μrad**
  - **Rectilinear position error directly proportional to distance**
    - **750 km at 1 AU**
    - **5 km at 1,000,000 km**
- **Angular accuracy not as great as with radio metric data; however,**
  - **Angles are measured directly, rather than inferred through processing of line-of-sight data**
  - **Angles are relative to target body, rather than Earth**
- **Downtrack position not sensed until spacecraft-target geometry changes appreciably**

Deep Space Navigation System

Functions: Measurement Acquisition, Flight Path Determination, Maneuver Computation and Command



Planetary Ephemerides

Dynamic Models

Calibrations

Earth Rotation

Station Locations

Observational Models

Predicted Observations

Compare

Flight Path Estimation

Data Fit OK?

No

Yes

Flight-Path Optimization

Ground Data Processing System

Guidance Commands

Observations

Mars

Sun

Solar Radiation

Solar Torques, Thruster Firings

Radio Metric Tracking

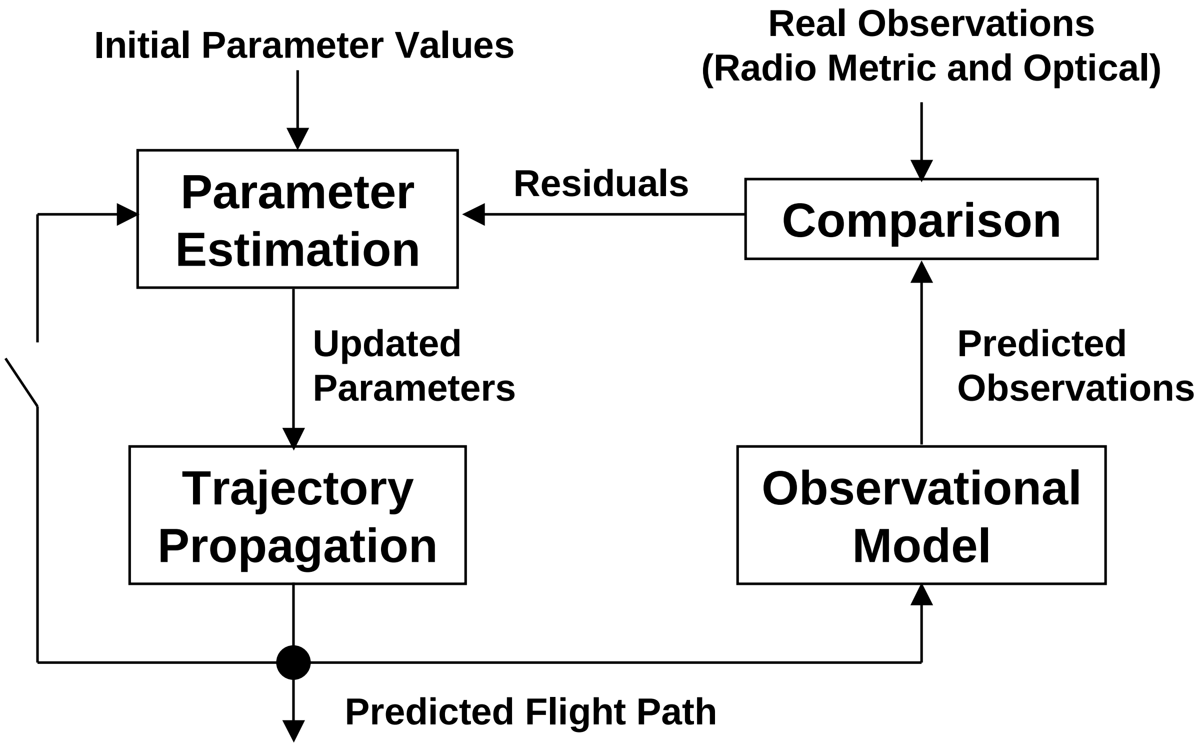
Ionosphere

Troposphere

Earth

Flight Path Estimation Block Diagram

- **Estimation process is performed by adjusting free parameters so as to minimize measurement residuals in some weighted-least-squares sense**
  - **Measurement accuracies and accuracies with which parameters were known before receiving measurements are taken into account**
- **Estimated parameters include**
  - **Spacecraft position and velocity at some reference time**
  - **Additional optional parameters:**
    - **Nongravitational accelerations**
    - **Discrete velocity changes**
    - **Planetary and satellite ephemerides**
    - **Gravity field characteristics**
    - **Tracking station locations**
    - **Measurement biases**



Initial Parameter Values

Real Observations (Radio Metric and Optical)

Parameter Estimation

Residuals

Comparison

Updated Parameters

Predicted Observations

Trajectory Propagation

Observational Model

Predicted Flight Path

Navigation System Software

- **DPTRAJ -- Trajectory Propagator**
  - **Integrates equations of motion (full set of acceleration models)**
  - **Allows detailed tuning of models via input**
  - **Generates S/C ephemeris file (P-file)**
  - **Passes S/C ephemeris to Orbit Determination Program (ODP)**
- **ODP -- Orbit Determination Program**
  - **Processes radio metric data (range, Doppler, VLBI, etc.) to produce estimates of state, maneuvers, and astrodynamic and geophysical parameters**
  - **Performs nonlinear estimation for specific modeled parameters via various filtering strategies**
  - **Produces statistical estimates for estimated parameters and maps solutions to target space**
  - **Calculates covariance and sensitivity matrices for all parameters estimated**

Navigation System Software (Continued)

- **MOPS -- Maneuver Operations Program**
  - **Determines propulsive maneuvers and associated commandable quantities from S/C trajectory and characteristics**
  - **Predicts delivery accuracy to target**
  - **Determines optimized propellant utilization**
  - **Meets mission target requirements**
  - **Computes ideal Delta-V and maneuver start time**
- **NavUtils -- Navigation Utilities**
  - **Includes benchmarks, file comparison, file check, file compression, file creation, file dump, file format conversion, file identification, file merge, file print/plot, file update, file shorten, data scheduling, data simulation, etc.**
  - **Includes covariance analysis, DSN frequency/pointing predicts, planetary feature models, S/C antenna models, momentum desaturation models, physical constants, time conversion, etc.**

Navigation System Software (Continued)

- NavLibs -- Navigation Libraries
  - ~ 70 libraries
  - ~ 4000 subroutines
  - ~ 750,000 LOC (FORTRAN 77)
  - Portable
    - All Use NAVSYS
  - Reusable
    - Shared throughout system and among users
- NAVSYS Library -- System Dependent Functions
  - Colocates all computing system dependent features
  - Isolates system dependent features to single library on which other modules depend
  - Uses common IEEE definition for errors/exceptions
- Numerous other programs and modules not listed above

Navigation Software Migrations

- 1960s: IBM 704/7094 => Univac 1108
- 1970s: Univac 1108 => Unisys 1100
- 1980s: Unisys 1100 => DEC Vax
- 1980s: DEC Vax => SUN Sparc
- 1990s: SUN Sparc => HP 9000, DEC Alpha, SGI (General Unix)

Principal Error Sources in Radio Navigation

Error Source	Current Modeling Accuracy
Station Locations	
Crust-relative	5 cm
Pole location	5 cm
Timing (UTC)	0.5 ms
Media	
Ionosphere (X-Band, 8.4 GHz)	5 cm
Troposphere	4 cm
Ground Instrumentation	
Station oscillator	10^{-14}
Hardware range delays	0.5 - 1 m
Dynamics	
Nongravitational acceleration of spacecraft	10^{-12} - 10^{-11} km/s^2

Nongravitational Accelerations -- Impact on Navigation Performance

- **Unmodeled nongravitational accelerations can significantly affect spacecraft trajectories**
  - **For example, acceleration of 10^{-10} km/s^2 can shift trajectory by**
    - **0.37 km in 1 day**
    - **37 km in 10 days**
    - **3700 km in 100 days**
- **Unmodeled nongravitational accelerations can also significantly degrade spacecraft trajectory estimates**
  - **Failure to model nongravitational accelerations corrupts estimates of other parameters, such as position and velocity at epoch**
  - **New position and velocity estimates, when integrated, result in substantially displaced trajectory**

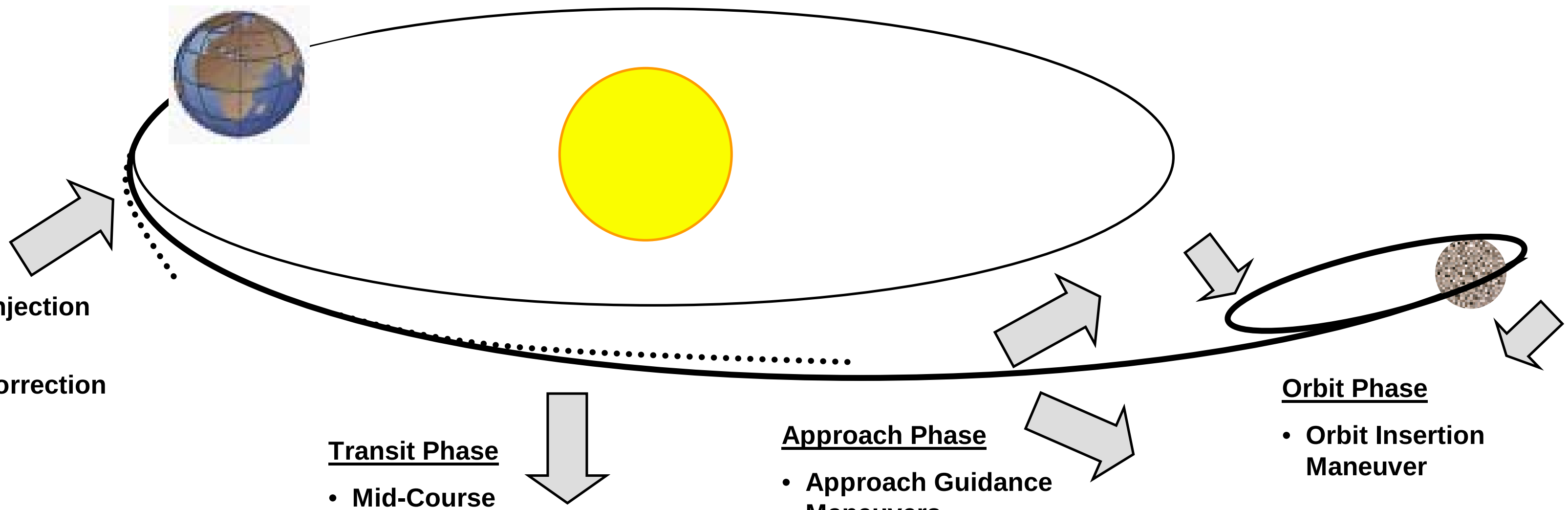
Planetary Ephemerides

- Planetary ephemerides are developed at JPL in continuous long-term activity; team and its charter are unique
- Orbits are refined using measurements from variety of sources
  - Radar measurements from Earth
  - Astrometric images
  - Radio signals from spacecraft near planet of interest
- Technical challenges in calculation of ephemerides include:
  - Obtaining long data arcs (on order of centuries)
  - Adjusting dynamical models
  - Determining consistent frame ties from celestial references to solar system bodies
- Typical planetary ephemeris accuracies
  - Mars at 2 AU: 10 nrad (3 km)
  - Neptune at 30 AU: 500 nrad (2300 km)

Planetary Ephemeris Verification

- There are four classes of checks of planetary ephemerides used by navigation teams
  - Examine pre-fit residuals of data sets incorporated into solution
  - Compare new ephemerides with previous ephemerides
  - Examine post-fit residuals of data sets incorporated into solution
  - Independent verification by various users prior to official release

Trajectory Control



Launch Phase

- **Interplanetary Injection Maneuver**
- **Launch Error Correction Maneuver**

Transit Phase

- **Mid-Course Maneuver**

Approach Phase

- **Approach Guidance Maneuvers**

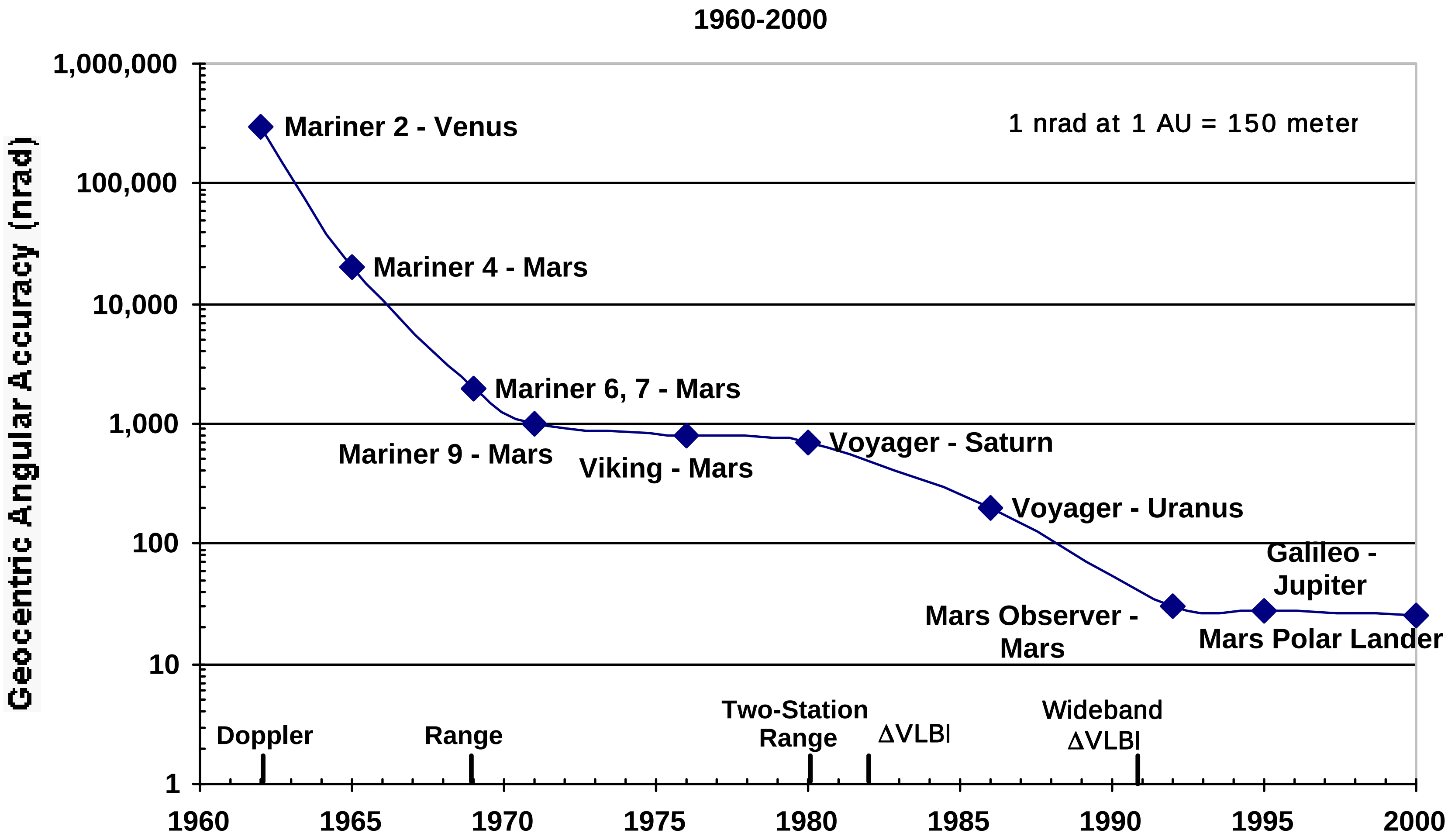
Orbit Phase

- **Orbit Insertion Maneuver**

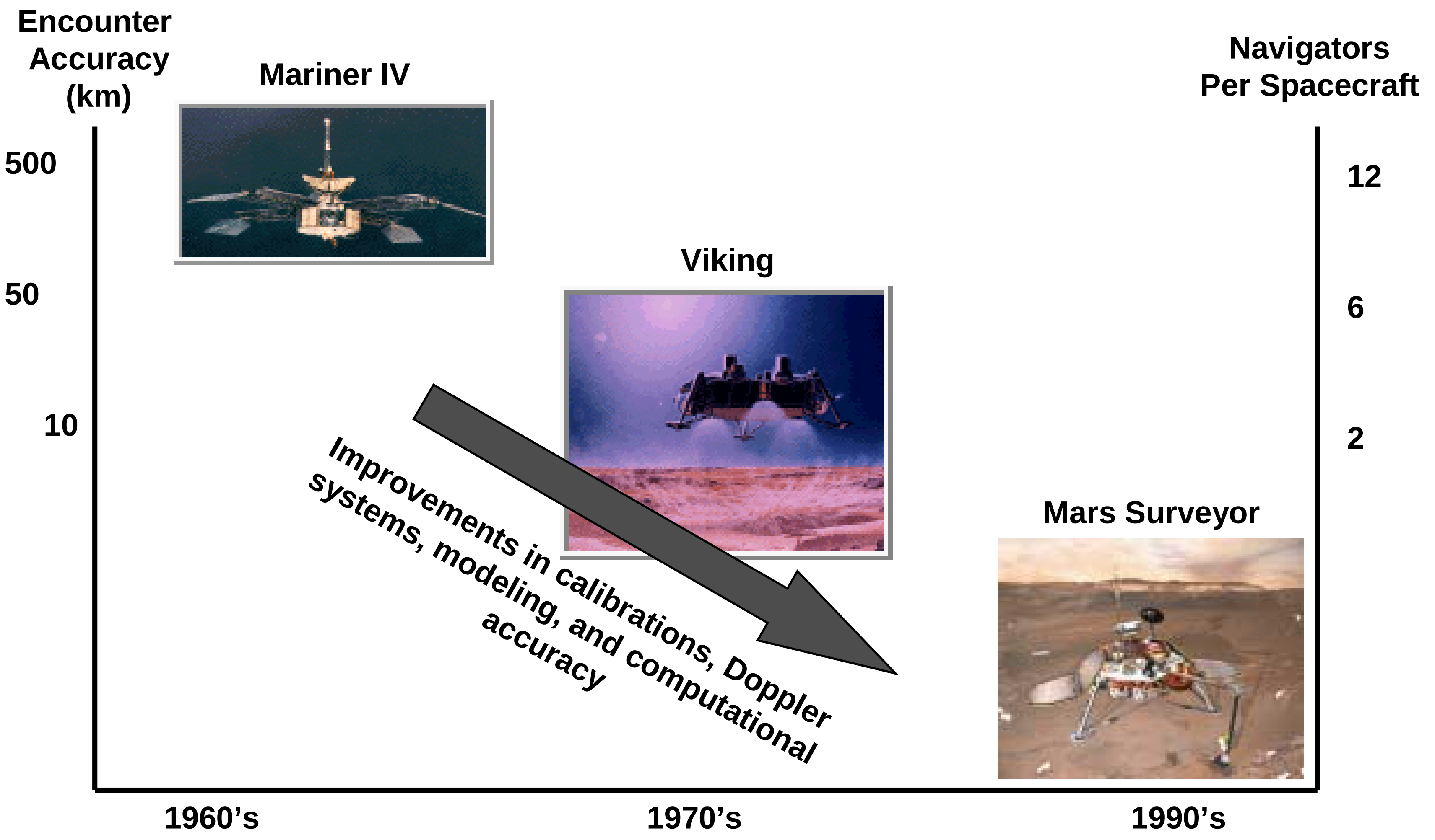
In typical interplanetary trajectory, depicted here, propulsive maneuvers are required to correct injection errors, make small orbit changes at mid-course and final approach, and achieve final trajectory at planetary target

Note: Figure not drawn to scale

Deep Space Navigation System:
Evolution of DSN Navigation System Accuracy



Benefits of Improved Radio Navigation Accuracy to Mars Missions



Encounter Accuracy (km)

500

50

10

Navigators Per Spacecraft

12

6

2

Mariner IV

Viking

Mars Surveyor

Improvements in calibrations, Doppler systems, modeling, and computational accuracy

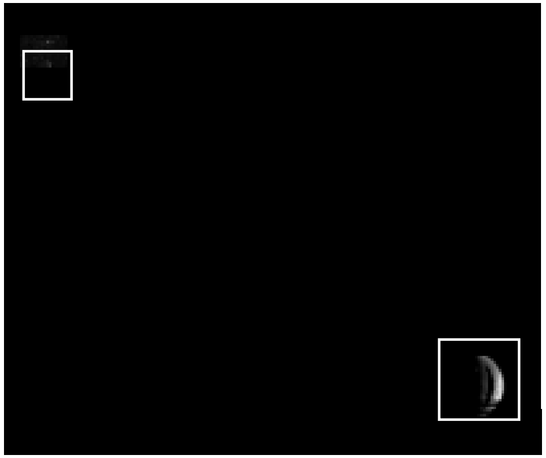
1960’s

1970’s

1990’s

Benefit of Optical Navigation to Voyager Science

By taking distant optical navigation images such as this on Voyager, orbit determination accuracies improved dramatically,



Sample OPNAV (Optical Navigation) Image

Triton Mosaic -- Made Possible in Part by Optical Navigation

allowing high-resolution science frames near satellite encounters such as this to become possible...

Without optical navigation, Voyager mission would have returned only on order of 10% of high-resolution science that it did return

Distinguishing Features of Deep Space Navigation Relative to Earth Orbital Navigation

- **Relative accuracy requirement usually much greater -- typically few parts in 100,000,000**
- **Target body ephemeris errors represent significant error source**
- **Targets of interest usually approached from unbound orbits**
- **Measurement data types must be more accurate or are unique**
  - **Random and systematic errors in Doppler and ranging data must be smaller**
  - **Interferometric and optical data types have no direct counterparts**
- **Information content of data types common to both applications is different, due to large differences in topocentric distances**
- **More complete and accurate dynamic and measurement modeling is needed**

Drivers for Enhanced Navigation Capabilities

- **Flight path accuracy (prediction, control, and reconstruction)**
  - **Single spacecraft relative to natural body (or its surface features)**
  - **Multiple spacecraft relative to one another**
- **Resiliency**
  - **Risk reduction through availability of complementary navigational techniques**
- **Efficient use of resources**
  - **Spacecraft propellant**
  - **Tracking time**
  - **Operations workforce**

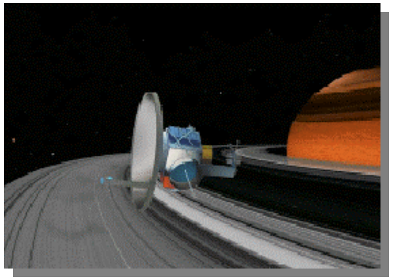
Navigation Challenges

- **Future missions involve new dynamic scenarios such as precision landing, aerocapture, and formation flying; this leads to two fundamental navigation challenges:**
  - **To expand our capabilities, navigation tasks need to be conducted with much less a priori knowledge about target body than in past and without constraint of round-trip light travel time**
    - **Key to extending navigation capability is to introduce powerful new types of navigation measurements, combined with reliable on-board navigation**
  - **Interplanetary navigation has always dealt with large differences between radial and angular component accuracy; radial information is obtained through direct measurements, but angular information is usually inferred over time and is dependent upon accuracy of dynamic and observational modeling**
    - **Key to improving navigation resiliency is to narrow gap between radial and angular uncertainty while providing multiple means of obtaining navigation solutions**

Navigation Challenges -- Extension of Capabilities

- **For several classes of new missions, shape and topography of target are unknown and/or changing rapidly**
  - **Surface and sub-surface navigation on Europa**
  - **Precision landing on comets and asteroids**
  - **Navigating near rings of Saturn**
  - **Aircraft navigation at Mars**
- **Also, many future missions require navigation updates on order of seconds (or faster), and thus, cannot be done via Earth:**
  - **Aerocapture**
  - **Precision landing**
  - **Rendezvous and docking**
  - **Rapid in-situ navigation**

Sub-surface Navigation



Planetary Ring Navigation

Mars Aircraft Navigation

Need for Operational Efficiency

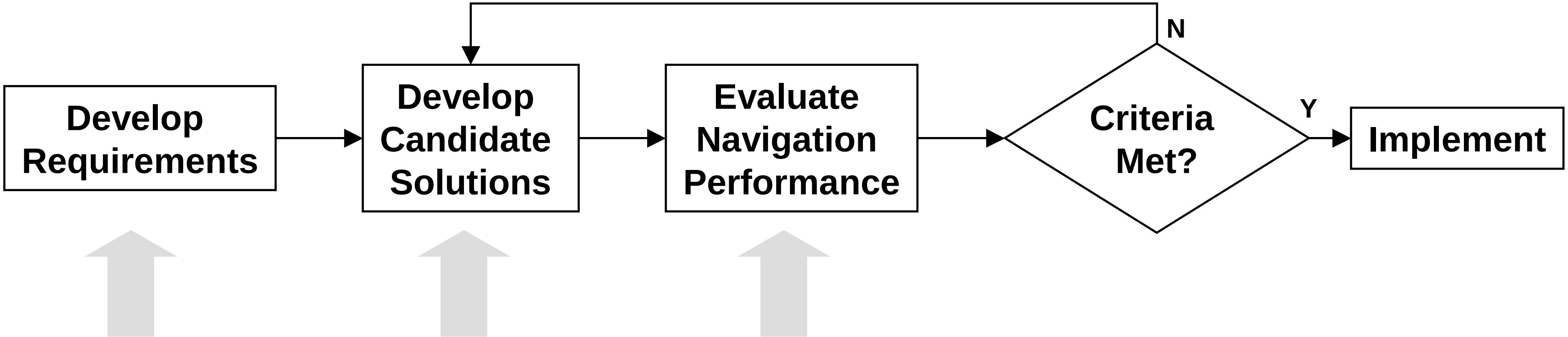
- **Large potential growth in number of vehicles requiring navigation services**
  - **Long-term vision for Mars exploration includes large number of vehicles in orbit or on or near surface at same time**
  - **Increasing number of Earth-orbiting scientific satellites for which JPL provides navigation services**
- **Quantity of vehicles motivates desire for**
  - **Less Earth-based tracking per vehicle**
  - **Greater on-board autonomy/reduced ground operations effort**

Areas of Focus for Improving Navigation Accuracy, Resiliency, and Efficiency

- **Measurement systems for determining flight paths**
- **Computational techniques and software for determining flight paths**
- **Computational techniques and software for controlling flight paths**

Navigation System Engineering

- **Given a particular navigation challenge, the following method is used to develop and evaluate candidate system solutions:**



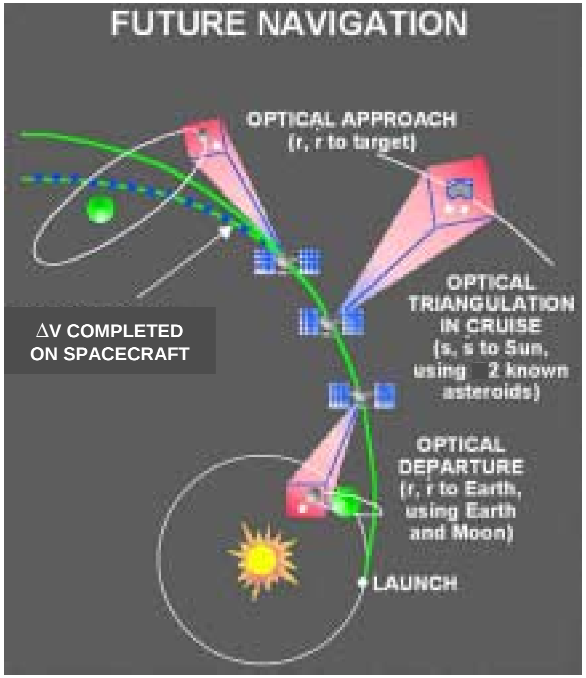
Present, future projects

Dialogue with spacecraft engineering, DSN, etc.

Performed with simulations, modeling

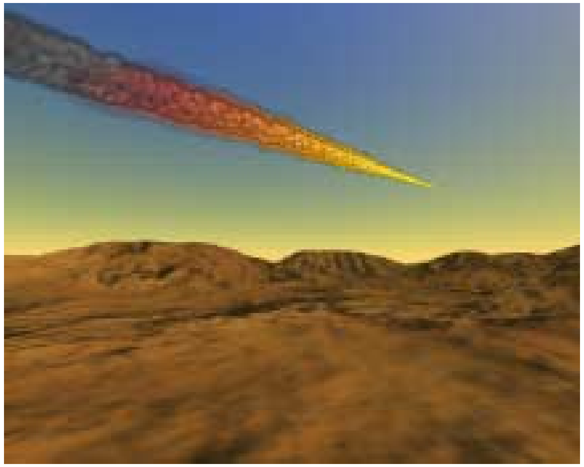
Performance criteria include:
- **Accuracy**
- **Turn-around time**
- **Processing load**
- **Size of navigation team**
- **Robustness**
- **Resource demands**
- **Applicability to other missions**
- **Cost**

New Mission Scenarios That Pose Navigation Challenges



Autonomous Navigation

Interplanetary cruise, flybys, and orbiter scenarios for all missions



Aerocapture

Missions going into orbit about Venus, Mars, Saturn, Uranus, Neptune

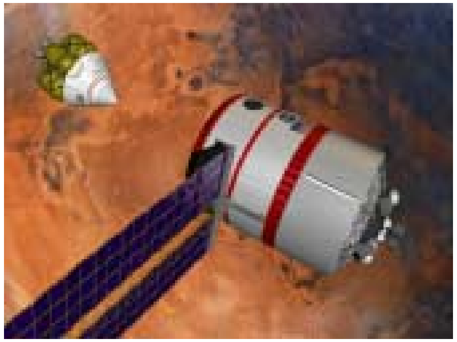
Precision Landing

Landing on or hovering near small bodies, terrestrial bodies, or planetary satellites

New Mission Scenarios That Pose Navigation Challenges (Continued)

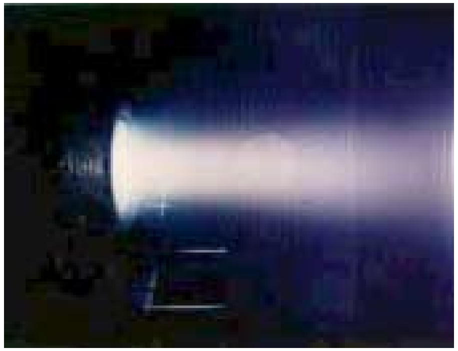
Multi-Vehicle GN&C

Mars constellations, formation flying, etc.



Rendezvous & Docking

Sample return missions to terrestrial planets, small bodies, and planetary satellites



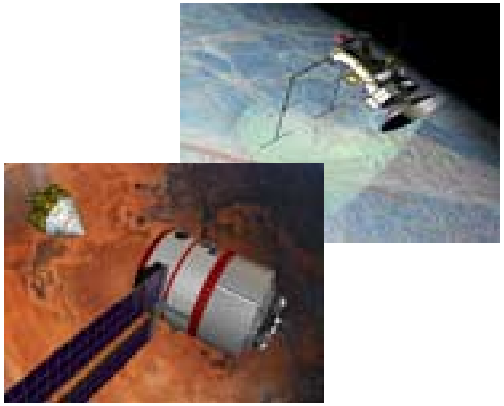
Low-Thrust Guidance & Navigation

Mercury, small body, and outer planet missions

***In-Situ* Vehicle GN&C**

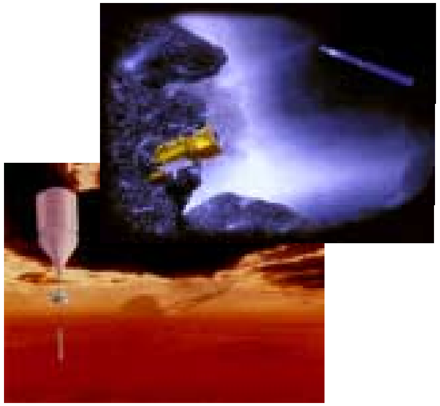
Rovers, balloons, submarines, and aircraft, on planets, satellites, and small bodies

Deep Space Navigation Roadmap



Deep Space Navigation Autonomy
Autonomous Rendezvous and Docking
Aerocapture

Mars ‘03 -’05
Europa Orbiter
Pluto/Kuiper Express
Deep Impact



Precision Landing
Multi-Vehicle GN&C
Low-Thrust GN&C
***In Situ* Vehicle GN&C**

Venus Sample Return
Mars Networks
Europa Lander
Neptune / Triton Orbiter
Titan Organics Explorer
Comet Nucleus Sample Return
Terrestrial Planet Finder

Autonomous *In Situ* GN&C
In-Orbit Hazard Avoidance
Small Body Modeling
Advanced Formation GN&C

Mars Robotic Outposts
Deep Atmospheric Probes
Saturn Ring Observer
Satellite Robotic Outposts
Asteroid Sample Return
Terrestrial Planet Imager

Advanced *In Situ* GN&C
Solar-Sail Navigation

Permanent Colonies
Satellite Sample Return
Interstellar Precursors

Timeline 2000 2005 2010 2015 2020 2025

Navigation to all regions of the solar system and beyond

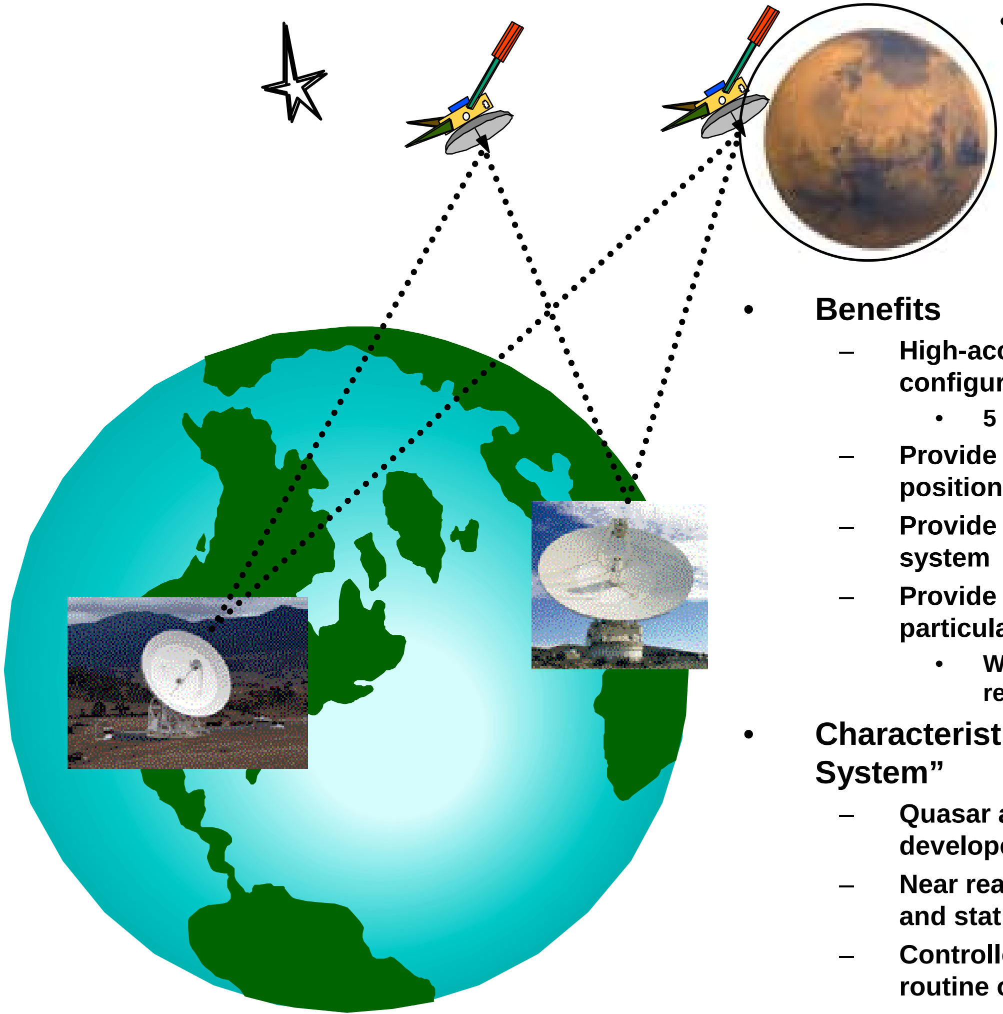
Extending Navigation Capabilities -- Solutions

- There are three classes of technologies that can extend navigation capabilities:
  - Advanced on-board measurements
    - Spacecraft Transponding Modem (STM)
    - Autonomous Formation Flyer (AFF) sensor
    - Optical for imaging and comparing landmarks
    - LIDAR for precisely measuring topography
    - Advanced, compact Inertial Reference Units (IRUs)
  - Remote spacecraft networks
    - Orbiting or surface assets at remote bodies could aid spacecraft before and after arrival
  - Navigation software to support autonomy
    - High-fidelity navigation system incorporating new algorithms capable of handling advanced on-board and Earth-based measurements

Improving Angular Component Accuracy -- Solutions

- **There are four classes of solutions that can improve angular accuracy, and thus, improve navigation resiliency:**
  - **Streamlined interferometric measurements**
    - **Interferometric measurements have been used in past; challenge is to make them more reliable and cost effective**
  - **Optical measurements**
    - **Optical measurements are used when compatible on-board hardware is available**
    - **Challenge is to come up with standardized low-mass optical navigation system to provide these measurements for all missions**
    - **Proposed autonomous optical navigation system addresses this challenge**
  - **Remote spacecraft networks**
    - **Orbiting or surface assets at remote bodies could aid spacecraft before and after arrival; challenge is to make these networks low cost and dependable**
  - **Dynamically ‘quieter’ and better-modeled spacecraft**
    - **Challenge here is to improve navigation advocacy in design of future spacecraft**

Streamlined Interferometric Measurements



- **Overview**
  - **DDOR (Delta-Differential One-way Range) and DDR (Doubly Differenced One-way Range)**
    - **Use 2 spacecraft (DDR) or one spacecraft and quasar (DDOR)**
    - **Require 2 DSN antennas (one at each complex)**
  - **Standardization of spacecraft hardware needed for full utility**
- **Benefits**
  - **High-accuracy: 5 to 50 nrad possible in ~ 1-hr pass, depending on configuration**
    - **5 nrad = 750 meters @ 1 AU**
  - **Provide independent and reliable measurement of spacecraft position**
  - **Provide performance assessment after fact to monitor navigation system**
  - **Provide needed backup capability to conventional Doppler/ranging, particularly where systematic errors are present**
    - **Where tight targeting is required, add measure of safety through redundancy**
- **Characteristics of streamlined "Next Generation DDOR System"**
  - **Quasar and/or S/C data recorded with Full Spectrum Recorders, developed for Galileo S-band Arraying**
  - **Near real-time signal processing using S/W correlator for quasars and station S/W phase extractor for S/C signals**
  - **Controlled remotely from JPL, monitored at stations; streamlined, routine operational capability for practicality**
  - **Reliability > 90%**

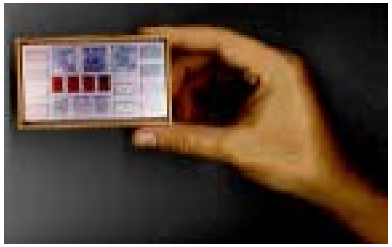
Near Simultaneous Tracking (NST)

- **Overview:**
  - **Analogous to DDR, but operationally different (non-simultaneous)**
  - **Requires two spacecraft**
- **Benefits:**
  - **Provides backup solution to verify other data types; adds robustness**
  - **When combined with other data types, improves navigation accuracy**
  - **Only requires 1 DSN antenna at time**
- **Issues:**
  - **Precision is variable and depends on stability of calibrations due to non-simultaneity of observations**
  - **Quality of navigation solution dependent on many factors**
  - **Need to implement routine operational capability**
  - **Technology exists for implementation**

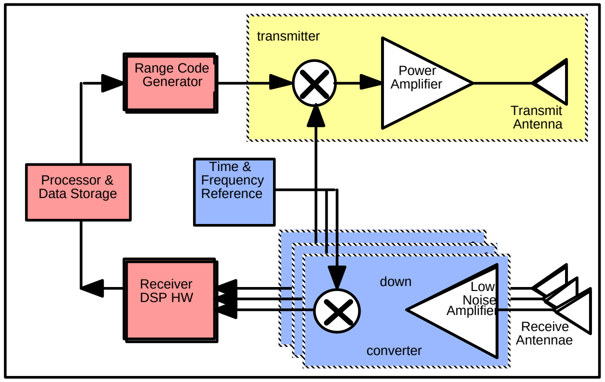
Autonomous Formation Flyer (AFF) Sensor

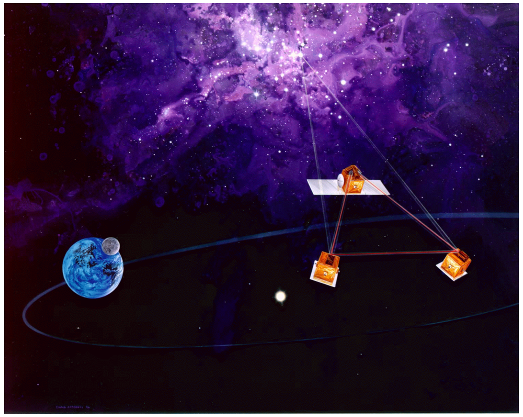
- Incorporation of inter-spacecraft ranging could support direct ultra-precise determination of relative spacecraft positions and clocks
- AFF is derived from JPL's GPS-On-A-Chip advanced space receiver; JPL has patented and is developing AFF instrument
- Applicable to Mars infrastructure satellites
  - Need to evaluate performance in Earth orbit
  - Need to develop 'light' AFF for in-situ users (rovers, landers, airplanes)

GPS-On-A-Chip



AFF

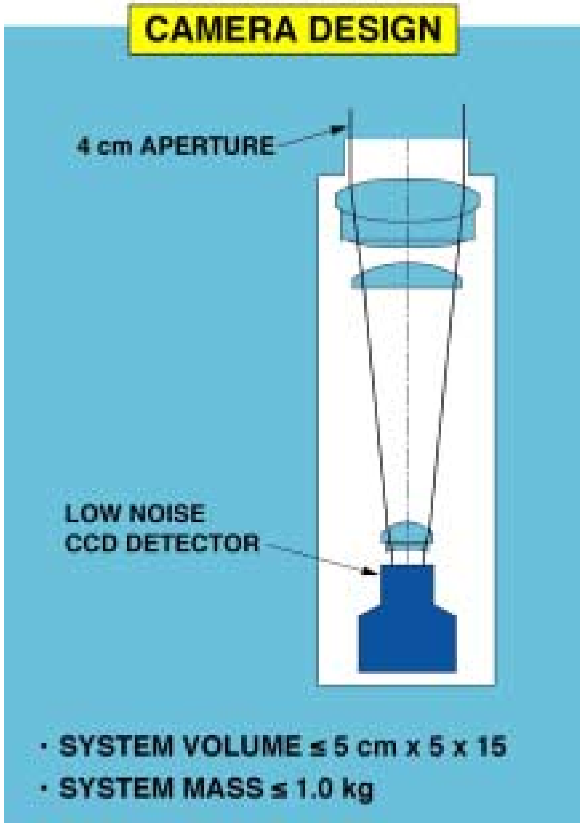




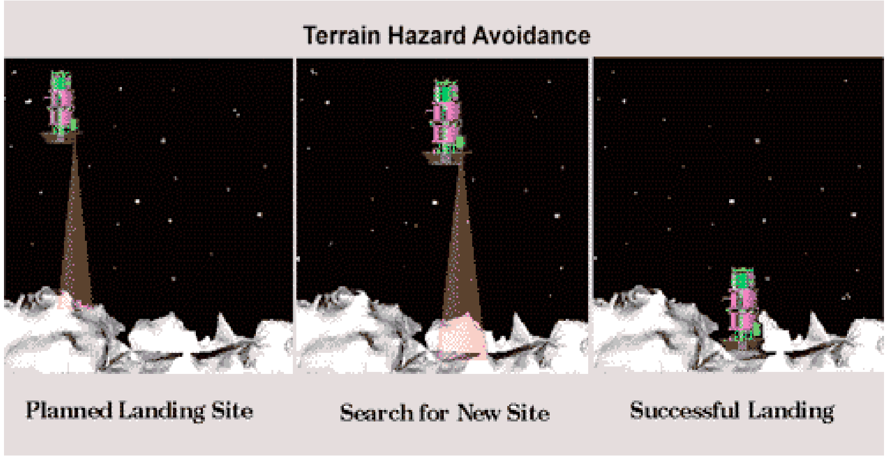
Separated spacecraft interferometer

Dedicated Optical Navigation Sensor

- **Based on passive imaging of starlight and sunlight reflected from target bodies**
  - **No Earth-based transmission required**
  - **No inter-spacecraft transmission required**
  - **Provides accurate target-relative navigation**
  - **System applicable to many mission types**
  - **Accesses fainter objects than star trackers with greater accuracy**
- **Final system will be designed to be integrated with main spacecraft avionics**
- **Benefits include:**
  - **Significantly decreases size of navigation operations teams**
  - **Virtually eliminates radio metric tracking requirements in some mission scenarios**
  - **Adds resiliency to navigation process**



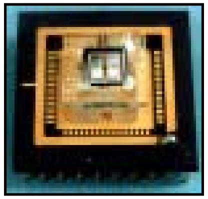
Advanced On-Board Measurements -- LIDAR



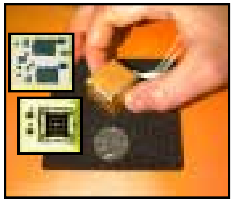
- **Description: On-board LIDAR system for quickly and accurately mapping topography**
- **Mission relevance: Enabling technology for precision landing at sites with unknown hazards, such as Mars, Venus, Europa, comets, and asteroids**
- **Technical navigation challenges: (1) Utilize LIDAR information to build up map of target body, (2) develop algorithms for autonomous real-time use of LIDAR data in terminal phase for hazard avoidance and final site selection**

Inertial Sensors

- **Overview:**
  - **Inertial Measurement Units (IMUs): 3 gyros & 3 accelerometers -- lander**
    - **Measure rotation angle changes and accelerations directly**
  - **Inertial Reference Units (IRUs): 3 gyros -- cruise**
    - **Measure rotation angle changes directly**
- **Benefits:**
  - **Real-time capability**
  - **Directly sense certain quantities that must otherwise be inferred through navigation fitting process (unmodeled accelerations)**
    - **Add measure of safety (but not necessarily redundancy)**
  - **Useful in cruise, EDL, and surface operations mission phases**
    - **Enables calibration of low-thrust engines or nongravitational accelerations due to angular momentum dumps or attitude control for unbalanced systems**
  - **Can compensate for direct tracking gaps**
- **Issues:**
  - **Cost, size, and mass vs. accuracy trades**
    - **Performance depends on calibration of drifts/biases**
  - **Need to integrate inertial measurements into navigation filtering**



μIMU ~ 2003
(1 deg/hr)



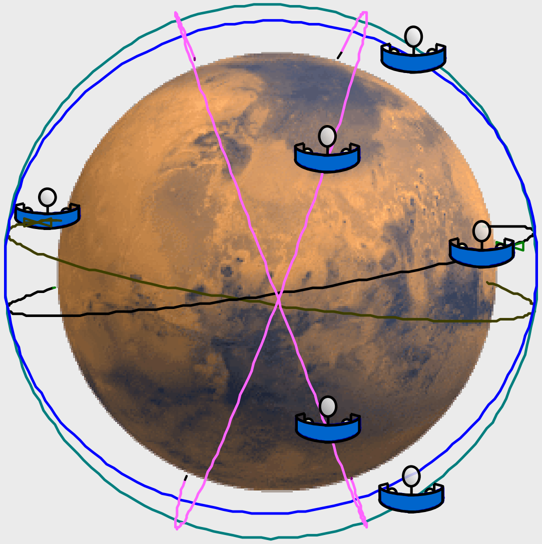
μIMU ~ 2008
(< 0.01 deg/hr)

Mars Infrastructure/Network

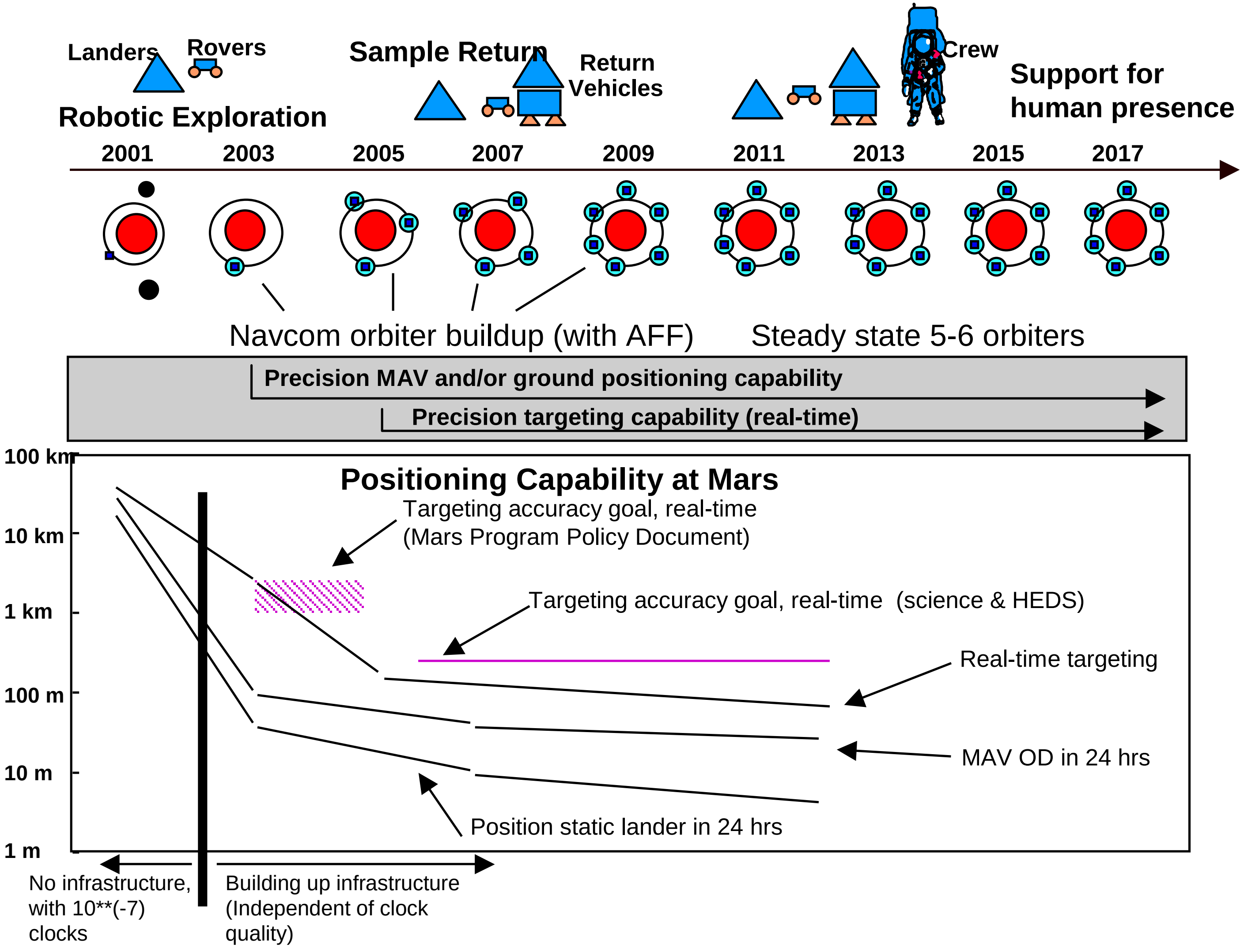
- **Overview:**
  - **Powerful in-situ GPS-like orbiting assets used for tracking, navigation, and telecom**
  - **Proposed six-satellite Mars Network constellation designed to optimize figures of merit such as mean response time and navigation performance**
- **Benefits:**
  - **Local measurements can provide 3-D trajectory information and additional measure of safety**
  - **Can provide 4π steradian visibility**
  - **Capable of very high accuracy**
  - **Can support real-time operations**
  - **Multi-mission support capability**
  - **Strong technology heritage from GPS experience at Earth**
  - **Also supports high-rate telecom**
- **Issues:**
  - **Availability limited primarily by infrastructure completeness**
  - **Need to optimize design & implementation plan for mission support during infrastructure build up and steady-state phases; constellation design must be optimized for both communications and navigation**
  - **Slower to implement and costlier than other resiliency options**

Candidate Mars Network Constellation

All Spacecraft at 800 km Altitude
2 S/C inclined at 172°
4 S/C inclined at 111°



Possible Mars Network Evolution



Landers

Rovers

Robotic Exploration

Sample Return

Return Vehicles

Crew

Support for human presence

Navcom orbiter buildup (with AFF)

Steady state 5-6 orbiters

Precision MAV and/or ground positioning capability

Precision targeting capability (real-time)

Positioning Capability at Mars

Targeting accuracy goal, real-time
(Mars Program Policy Document)

Targeting accuracy goal, real-time (science & HEDS)

Real-time targeting

MAV OD in 24 hrs

Position static lander in 24 hrs

No infrastructure,
with 10**(-7)
clocks

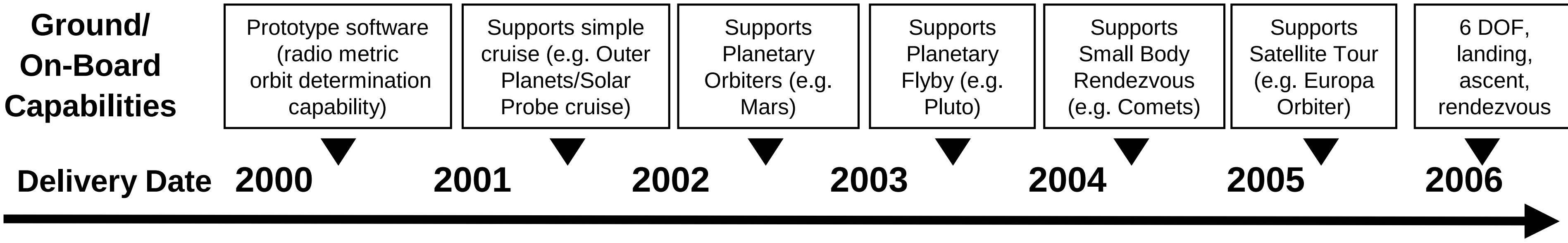
Building up infrastructure
(Independent of clock
quality)

Dynamically ‘Quieter’ and Better-Modeled Spacecraft

- **Paths to reduce spacecraft dynamical uncertainties:**
  - **Incorporate new transponder technologies**
    - **Spacecraft-to-spacecraft measurements (made possible by hardware such as Space Transponding Modem (STM))**
      - **Enables scenarios for reducing uncertainties of approaching spacecraft relative to orbiting spacecraft (at Mars, for example)**
      - **Enables formation flying or rendezvous of two or more spacecraft**
    - **Extraction of on-board tracking measurements**
      - **Enables on-board autonomy based on radio metric data**
    - **Differenced One-way Range (DOR) radio tones**
    - **Inertial Reference Unit (IRU) measurements**
  - **Enhance accelerometer accuracies**
    - **Calibration of low-thrust engines or nongravitational accelerations due to momentum dumps or attitude control using unbalanced thrusters enabled**
    - **Accelerometer measurements could be added to navigation filter**
  - **Collaborate with spacecraft designers on impacts to navigation operations**
    - **Navigation experts must be involved in spacecraft design process from beginning to assure that proper tradeoffs are made**
    - **Maneuver execution control with on-board closed loop (accelerometer) cutoff for magnitude and pointing precision**
    - **Momentum wheels (properly sized) to reduce thrusting frequency relative to bang-bang system**
    - **Balanced attitude thrusters (to few percent) to minimize non-gravitational acceleration**

Navigation Software to Support Autonomy:
Next Generation Navigation Software

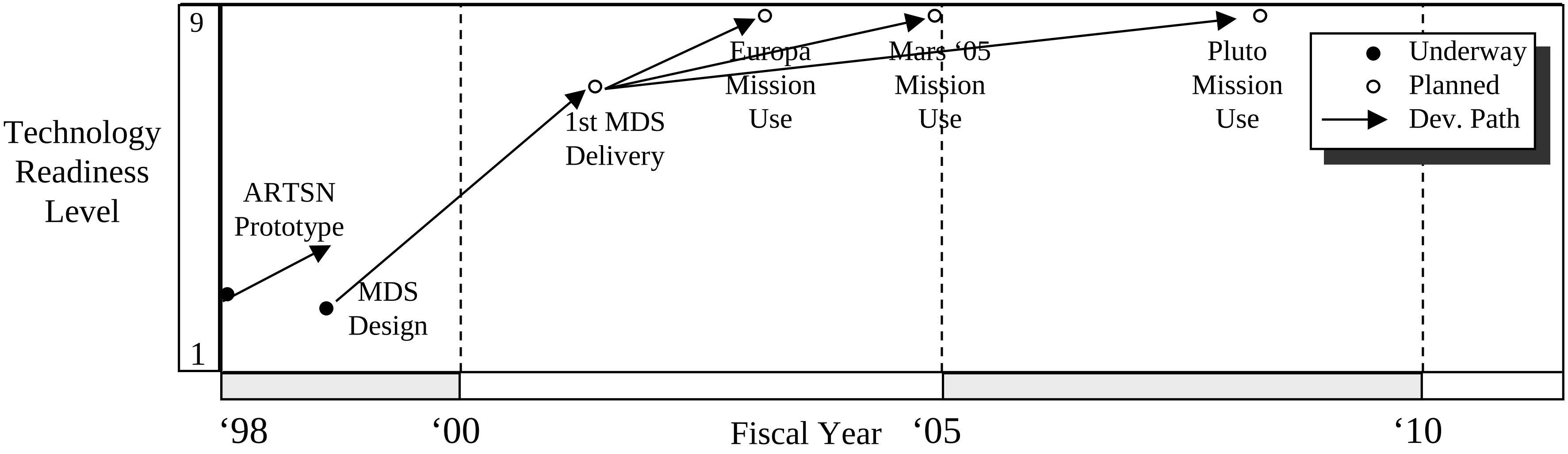
- **Program goals**
  - **Design, develop, implement, maintain, and evolve next generation software system for spacecraft navigation**
  - **Provide all trajectory-related functions in single, integrated system**
  - **Provide infrastructure for future system evolution**
  - **Incorporate state-of-the-art software engineering techniques**
- **Approach**
  - **Capture and retain existing capabilities (both ground and on board)**
  - **Add capabilities as needed for future missions**
- **Benefits include**
  - **Development enabled of integrated guidance, navigation, and control system for future missions**
  - **Decreased size of operations teams and improved productivity through automation**
  - **Decreased software maintenance cost and decreased cost for adding new features**
  - **Greater flexibility in coordinating mission activities between flight and ground systems**



Delivery Date	**Ground/ On-Board Capabilities**
2000	Prototype software (radio metric orbit determination capability)
2001	Supports simple cruise (e.g. Outer Planets/Solar Probe cruise)
2002	Supports Planetary Orbiters (e.g. Mars)
2003	Supports Planetary Flyby (e.g. Pluto)
2004	Supports Small Body Rendezvous (e.g. Comets)
2005	Supports Satellite Tour (e.g. Europa Orbiter)
2006	6 DOF, landing, ascent, rendezvous

Navigation Software to Support Autonomy: Next Generation Navigation Software (Continued)

- Strategy for migration of ground-based navigation functions to spacecraft flight system
  - Evolution driven by mission objectives, phases, and events
    - Start with well-understood phases such as interplanetary cruise
    - Gradually incorporate more complex phases and add new functions as needed by future missions
    - Align with evolution of overall flight system planner/resource manager
  - All primary navigation functions encompassed
    - Emphasis on trajectory estimation (orbit determination) and trajectory control (maneuver design)
    - Strong interaction with trajectory design and optimization
    - Auxiliary functions provide ephemeris and S/C clock-ground time correlation data to flight system



Acknowledgment

- **Some of the viewgraph material in this package was originally prepared by:**
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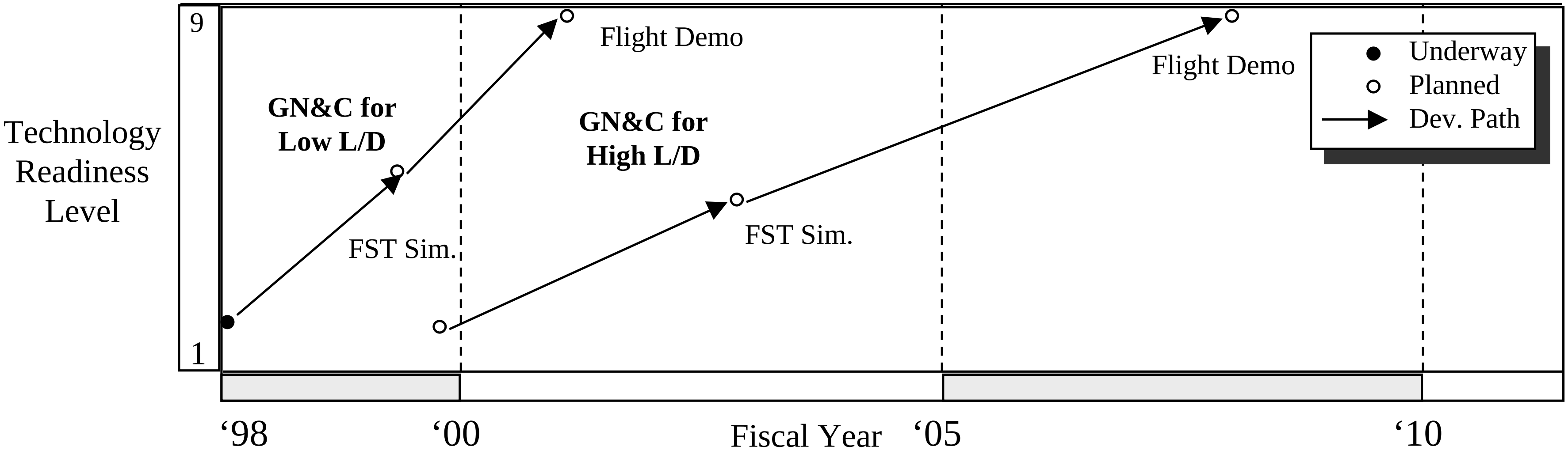
  - **Charles D. Edwards (901)**
  - **Joseph R. Guinn (312)**
  - **Stephen M. Lichten (335)**
  - **Michael M. Watkins (312)**

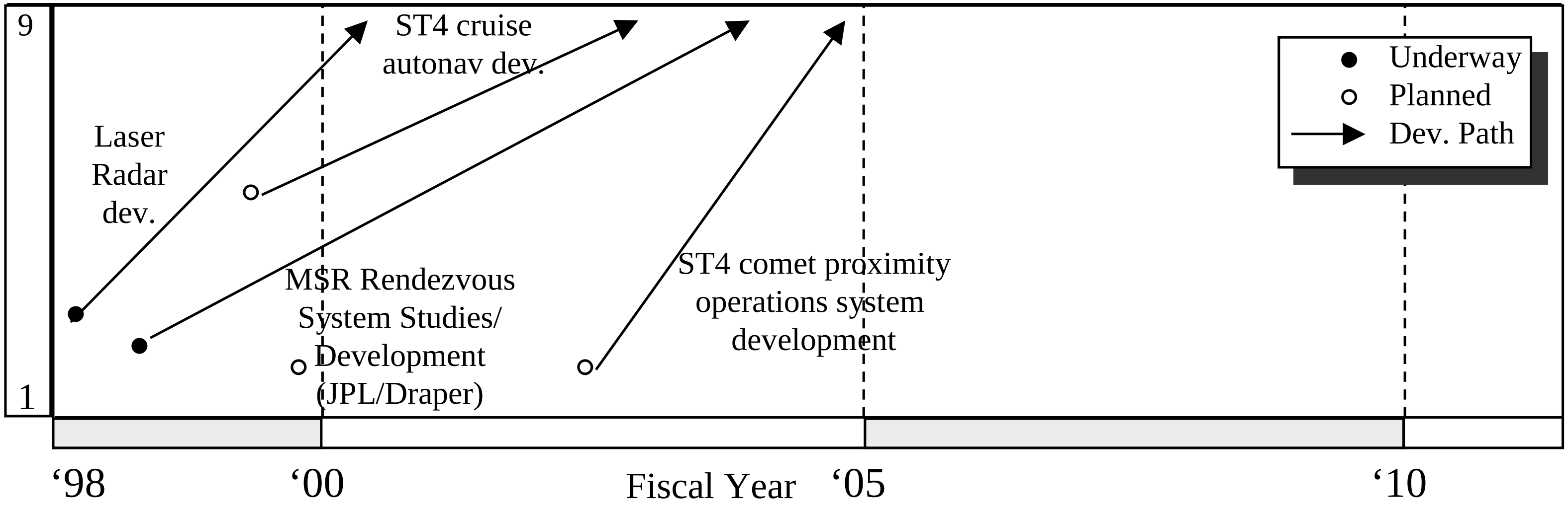
Autonomous GN&C Technology (Aerocapture/Aeromaneuver)

- **Approach navigation**
  - **Entry flight angle control to < 0.5 deg**
  - **Earth-based radio, on-board optical, inertial measurements**
- **Aerodynamics**
  - **Vehicle configurations (sphere/cone, bi-conic, winged, inflatable)**
  - **Aerodynamic force and torque estimation**
- **Aerothermodynamics**
  - **Flow-field analyses (CFD) still in development for simple configurations**
  - **New flow regimes, new gases, new configurations**
- **Validation**
  - **Ground tests, flight tests**



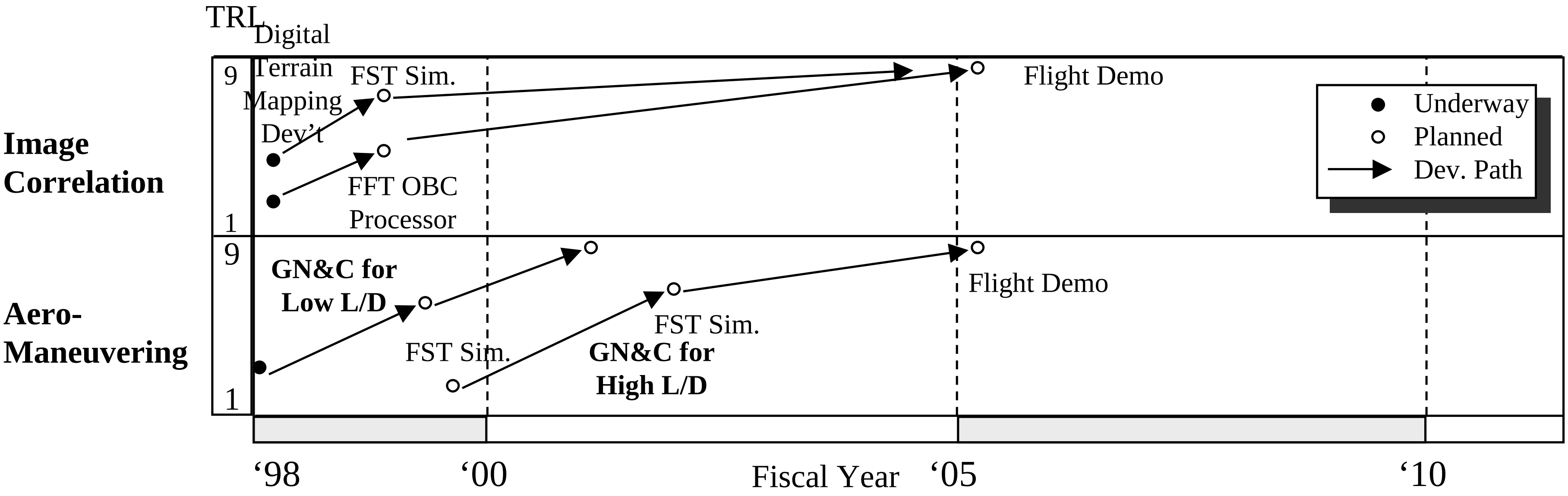
Autonomous GN&C Technology (Ascent, Rendezvous, and Docking)

- **Technical challenges**
  - **Accurate orbit determination of passive vehicles relative to active vehicle**
    - **Spacecraft-spacecraft orbit determination about body other than Earth**
    - **Diverse data types**
  - **Maneuver strategies to match orbits of active and passive vehicles**
    - **Unpredictable initial conditions (e.g., Mars aerobraking)**
    - **Constraints on propellant consumption and time**
  - **Development of ground software for rendezvous analysis**
  - **Development of onboard autonomous system for rendezvous and docking**
    - **Avionics, orbit determination and maneuver design algorithms**
    - **Flight software coding, validation, and integration**
  - **Laser radar**



Autonomous GN&C Technology (Precision Landing)

- **Technical challenges**
  - **Develop approach and entry phase control to reduce errors at parachute deployment to 5-10 km**
  - **Develop parachute phase navigation to achieve terrain-relative knowledge error of 100-200 m**
  - **Develop autonomous interpretation of real-time terrain images for obstacle avoidance and navigation**



Autonomous GN&C Technology (Small Planetary Bodies)

- **Technical challenges**
  - **Develop simple models to analyze navigation of satellite in close proximity to small body, using unified real-time position and attitude determination system**
  - **Makes it possible to implement, model, and analyze new ideas and approaches to autonomous navigation**
    - **Development of these models will aid in prediction of tracking profiles and allow for optimization of total cost of navigation, both ground-based and autonomous combined, instead of artificially separating these categories**
    - **Study reliance of autonomous navigation on ground-based navigation, and vice-versa**
    - **More realistic planning models and operation concepts can be developed for these future missions, incorporating true cost of all such proposed approaches**