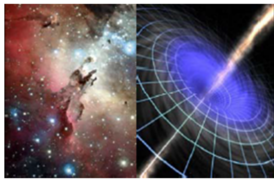

Курс лекций весеннего семестра 2011 года:

«Современные Проблемы Астрономии»

Государственный Астрономический Институт им. П.К. Штернберга

Lecture 9.0:

Basics of Spacecraft Navigation:

Principles, methods and observables

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Курс Лекций: «Современные Проблемы Астрономии»
для студентов Государственного Астрономического Института им. П.К. Штернберга
7 февраля – 23 мая 2011

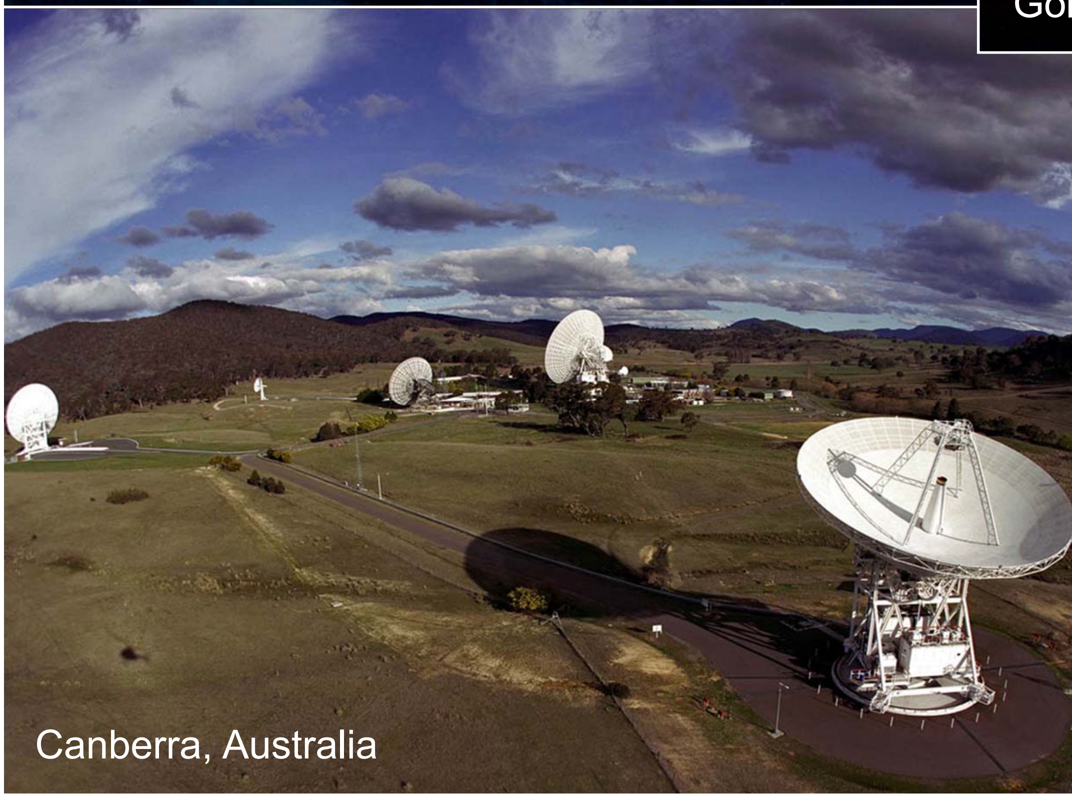
Outline

- Introduction
  – Mission design and navigational components
- Navigation measurements
  – Doppler
  – Range
  – Range-rate
  – Delta DOR
  – Other types
- Flight path estimation
- Flight path control
- Navigation accuracies

Deep Space Network


Goldstone, California


Goldstone, California


Canberra, Australia


Madrid, Spain

Typical Data Types for Spacecraft Navigation

Data Type	Characteristics	Current Accuracy	Typical Mission Phases
Doppler	Measures line-of-sight range rate	0.03 mm/s (60s)	All. Only data type used for Mars orbiting spacecraft and for certain astronomical observatories.
Range	Measures line-of-sight range	~1-2 m	LEOP, cruise, approach, planetary ephemeris updates
Angles	Measures plane-of-sky position	0.17 mrad 0.01 deg	LEOP, usable only in the proximity of the Earth
DDOR	Measures plane-of-sky position	2.5 nrad 0.14 μdeg	Cruise, approach, planetary ephemeris updates
Optical	Angular resolution down to about 0.1mdeg	1.7 μrad 0.1 mdeg	Approach, proximity, satellite ephemeris updates

DSN navigation is the state of the art in deep space nav technology

Navigation Tracking-Metrics Requirements (12/2007)

Tracking Error Source (1σ Accuracy)	units	current capability	2010 reqt	2020 reqt	2030 reqt
Doppler/random (60s)	mm/s	0.03	0.03	0.03	0.02
Doppler/systematic (60s)	mm/s	0.001	0.003	0.003	0.002
Range/random	m	0.3	0.5	0.3	0.1
Range/systematic	m	1.1	2	2	1
Angles	deg	0.01	.04	.04	.04
ΔVLBI	nrad	2.5	2	1	0.5
Troposphere zenith delay	cm	0.8	0.5	0.5	0.3
Ionosphere	TECU	5	5	3	2
Earth orientation (real-time)	cm	7	5	3	2
Earth orientation (after update)	cm	5	3	2	0.5
Station locations (geocentric)	cm	3	2	2	1
Quasar coordinates	nrad	1	1	1	0.5
Mars ephemeris	nrad	2	3	2	1

Mission Design Process Elements

- Mission design
  - Identify and gather general inputs/requirements
    - Science
    - Basic flight system constraints
  - Define, schedule, and clarify responsibilities for subprocesses
    - Mission planning/engineering process
    - Trajectory design process
    - Navigation accuracy analyses
  - Iterate with Project Management/Flight System Engineering

Mission Planning/Engineering Process

- Take general inputs, requirements, and constraints
- Develop scenarios/“concept of operations” for mission events
  - Development
  - Launch readiness
  - Flight operations
- Formulate baseline products and update with iterations
  - Trajectory
  - Mission design

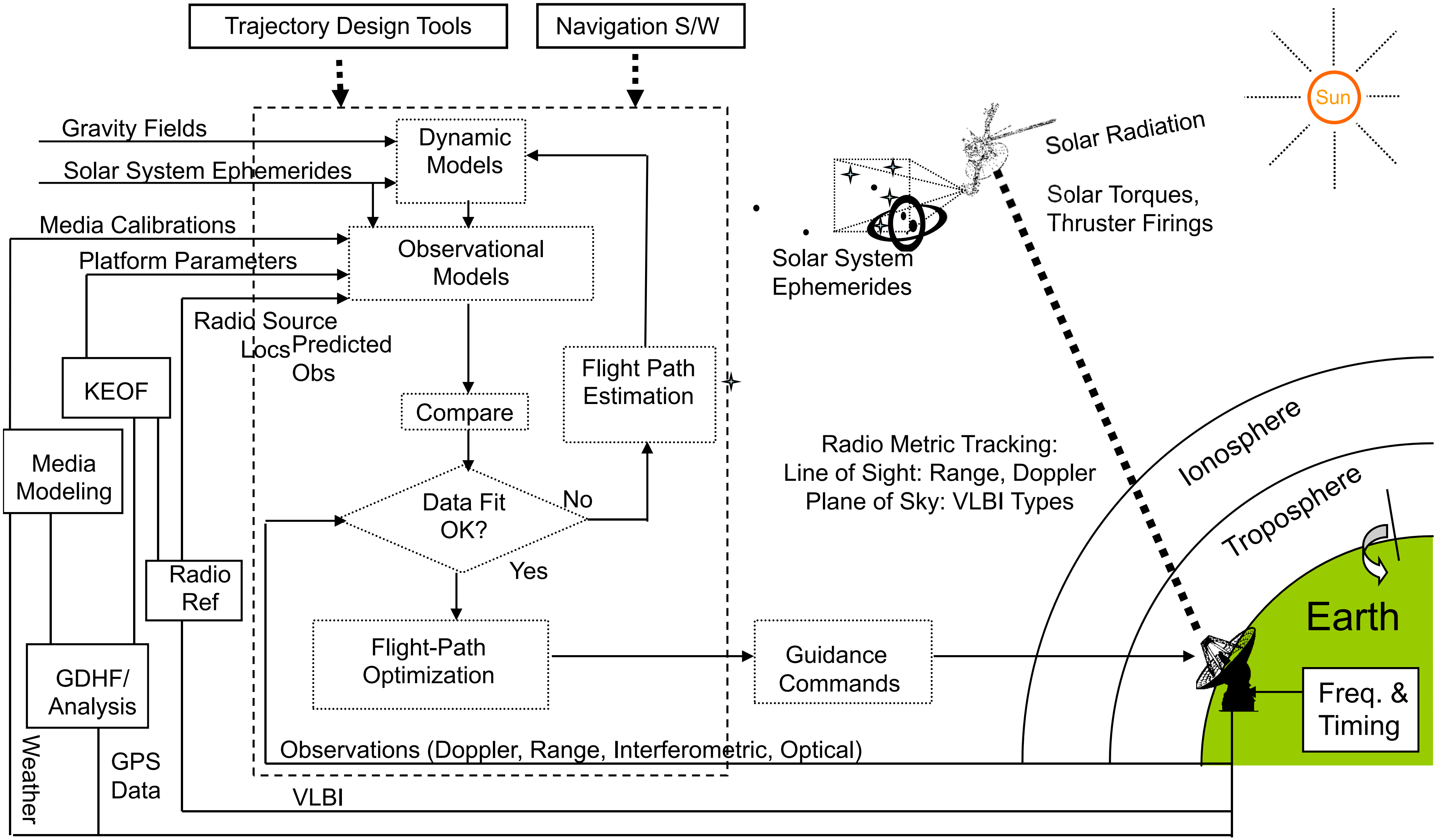
Mission Design and Navigation Components

These 5 tasks need to be performed for successful mission design & navigation:

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

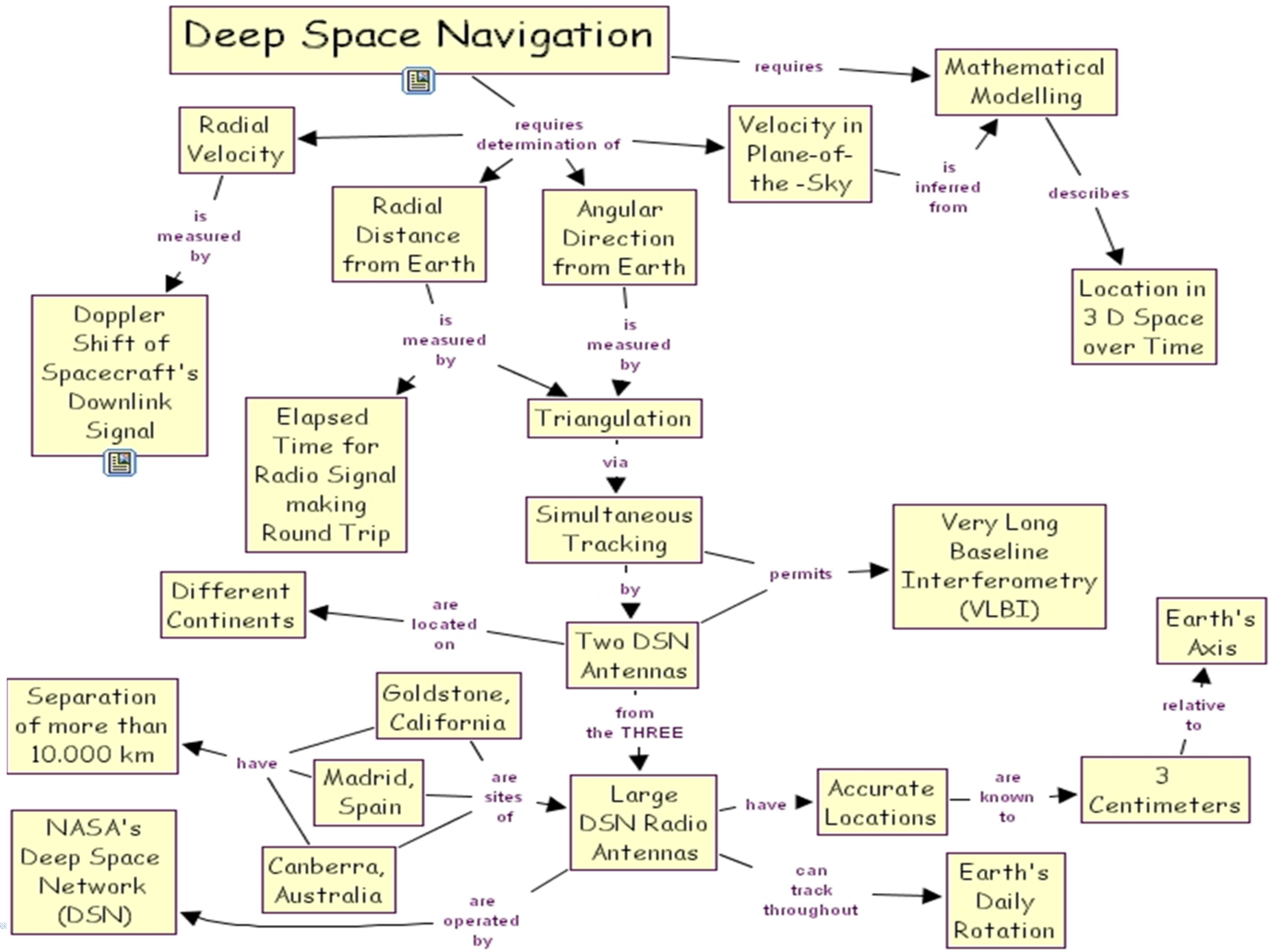
The Space Navigation Process



Navigation Accuracy Analyses

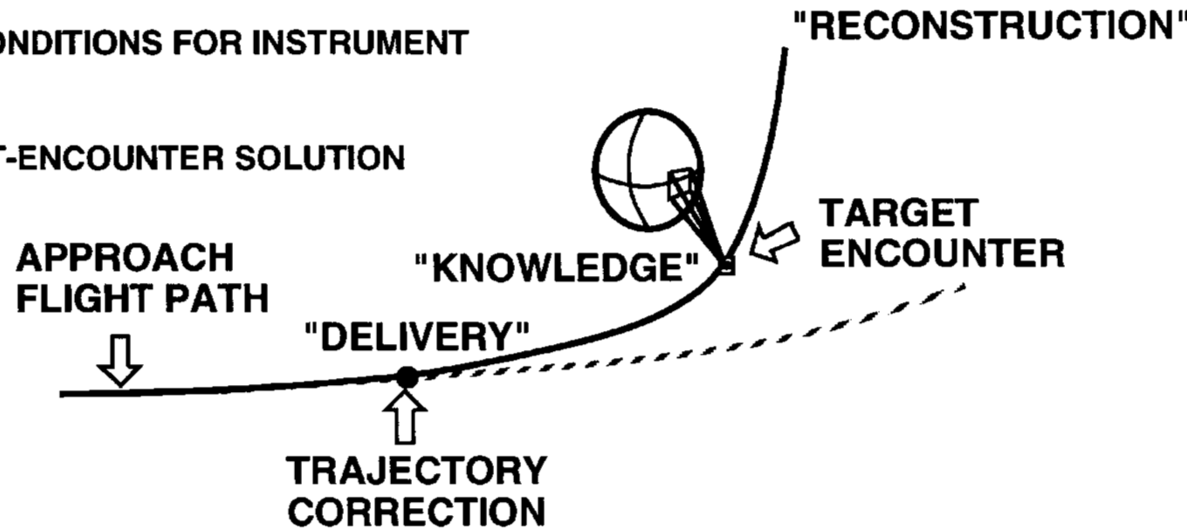
- Trade analyses (based on statistical analyses) performed to show
  - Navigation performance as a function of certain constraints
  - Requirements on overall flight/ground system needed to achieve certain navigation performance levels
- Significant inputs/assumptions
  - Tracking support
  - Navigation data types (Doppler, range, Delta-DOR, optical, LIDAR, etc.)
  - Media and geodetic uncertainties
  - Trajectory geometry
  - Dynamic activity on spacecraft (attitude maintenance)
- Significant products
  - Arrival statistics (“B-plane” statistics, flight path angle uncertainty)
  - Recommendations for changing above inputs

JPL DSMS Summary



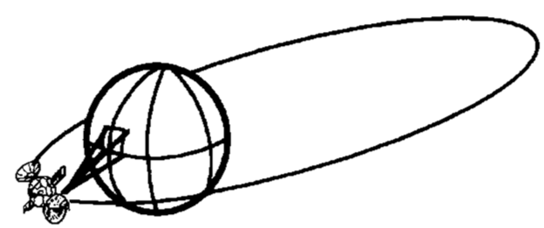
Navigation Objectives in Different Mission Phases

- **Flyby/orbit insertion:**
  - DELIVER SPACECRAFT TO DESIRED LOCATION AT DESIRED TIME
  - PREDICT ENCOUNTER CONDITIONS FOR INSTRUMENT POINTING/SEQUENCING
  - OBTAIN ACCURATE POST-ENCOUNTER SOLUTION

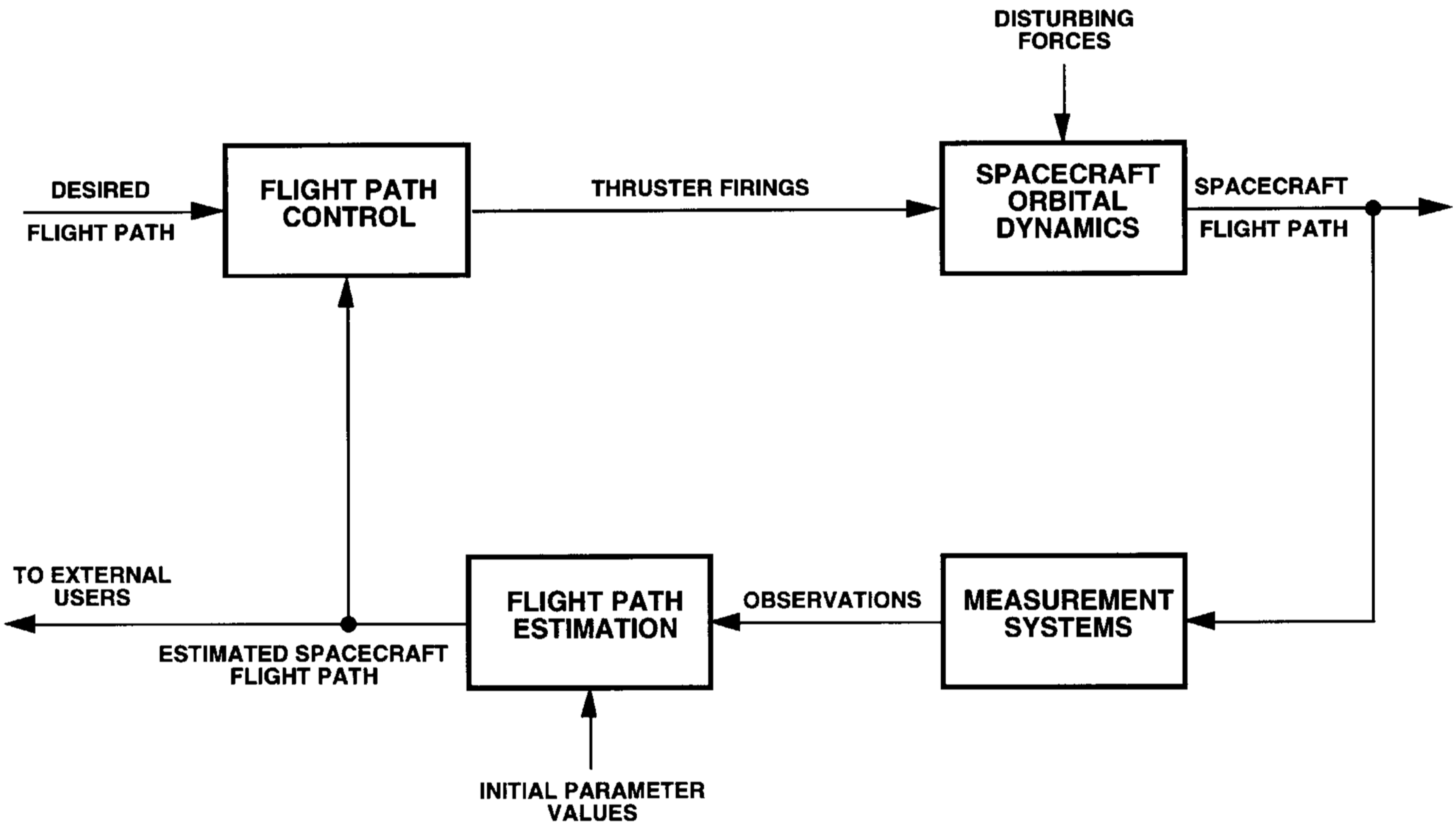


STEPS: MEASUREMENT ACQUISITION, ORBIT DETERMINATION, MANEUVER COMPUTATION AND COMMAND

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



Deep Space Navigation System Block Diagram



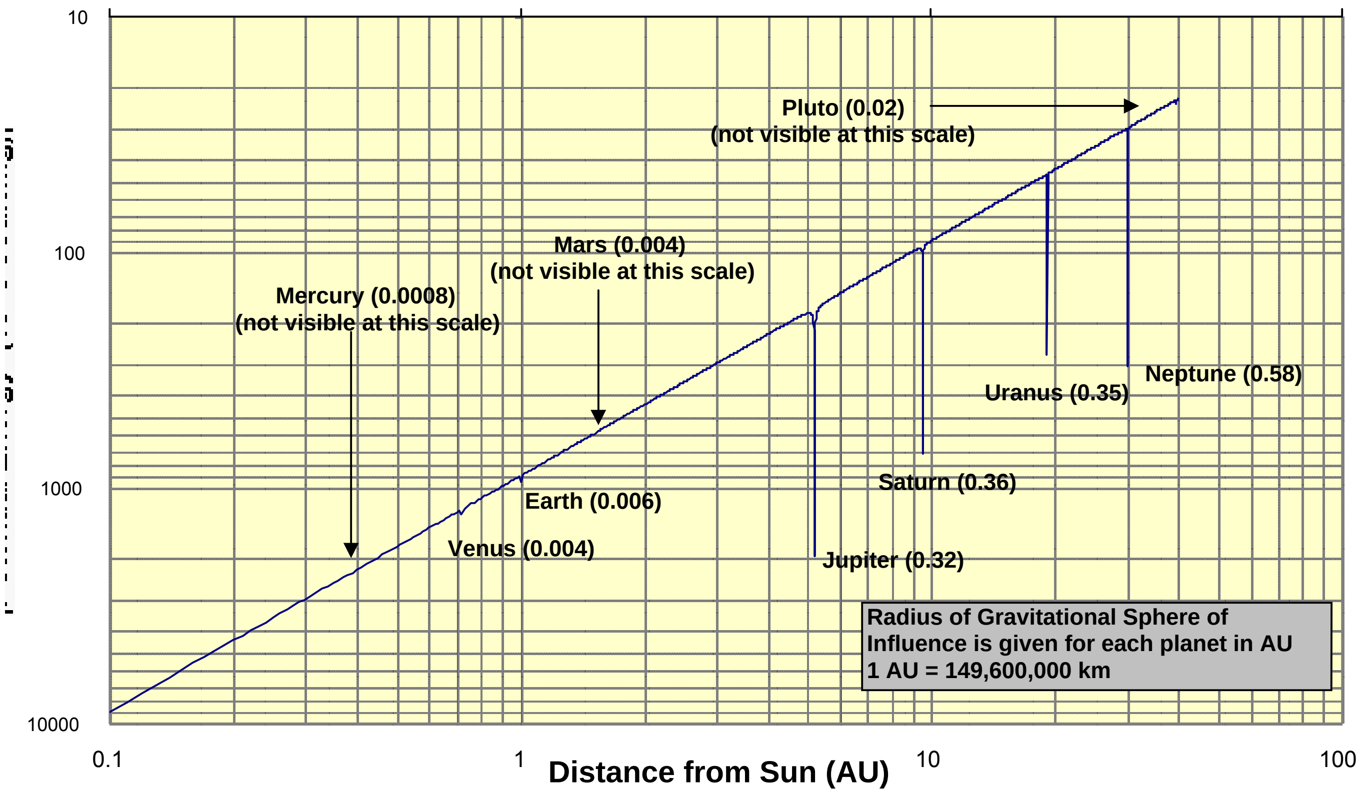
Spacecraft Orbital Dynamics

- Translational motion of spacecraft is determined by number of forces that act on spacecraft:
  - Gravitational forces on the spacecraft
    - 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
  - Non-gravitational forces
    - Thruster firings to control: a) trajectory and b) attitude
    - Gas leaks
    - Solar radiation pressure
    - Aerodynamic drag
    - New – thermal recoil forces due to heat momentum transfer

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

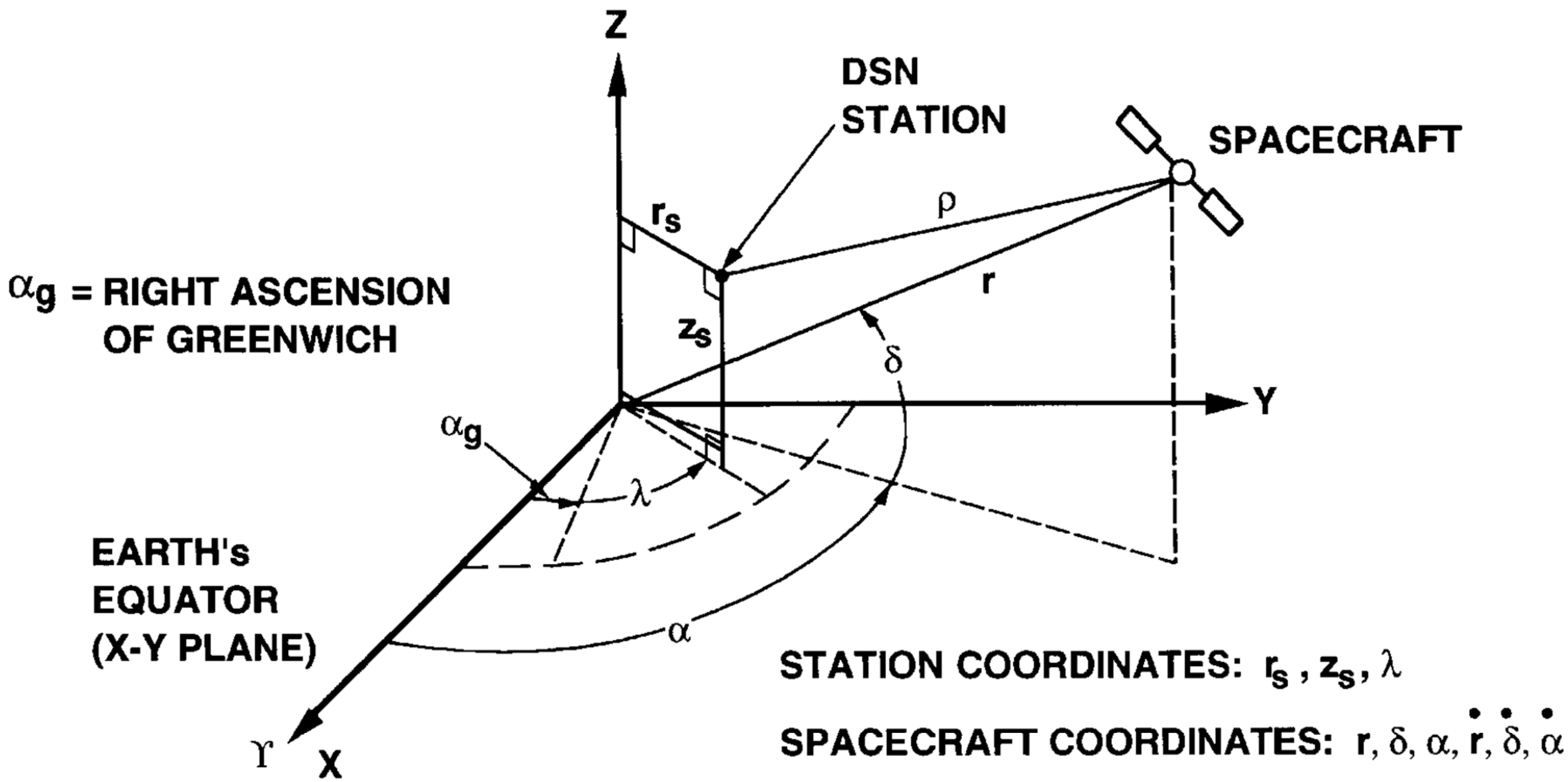
$r_{SOI} = a_p(\frac{m_p}{m_s})^{2/5}$ - sphere of influence



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



GEOCENTRIC SPACECRAFT COORDINATE DEFINITIONS:

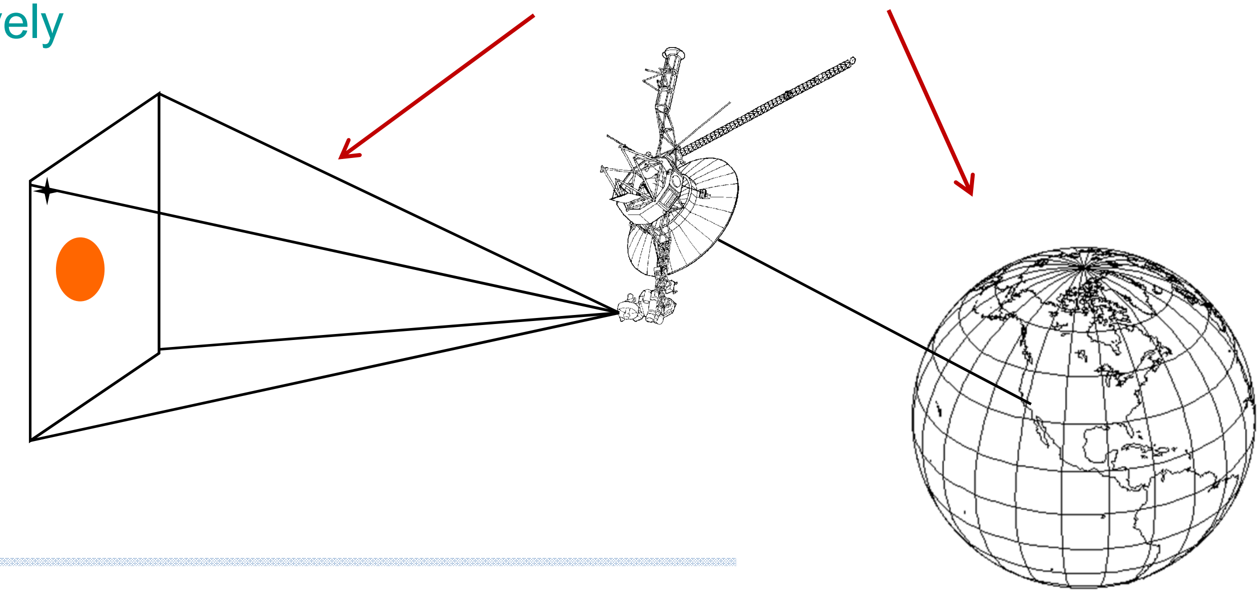
r = RANGE	δ = DECLINATION	α = RIGHT ASCENSION
$\dot{r}$ = RANGE-RATE	$\dot{\delta}$ = DECLINATION RATE	$\dot{\alpha}$ = RIGHT ASCENSION RATE

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

http://ssd.jpl.nasa.gov/?horizons

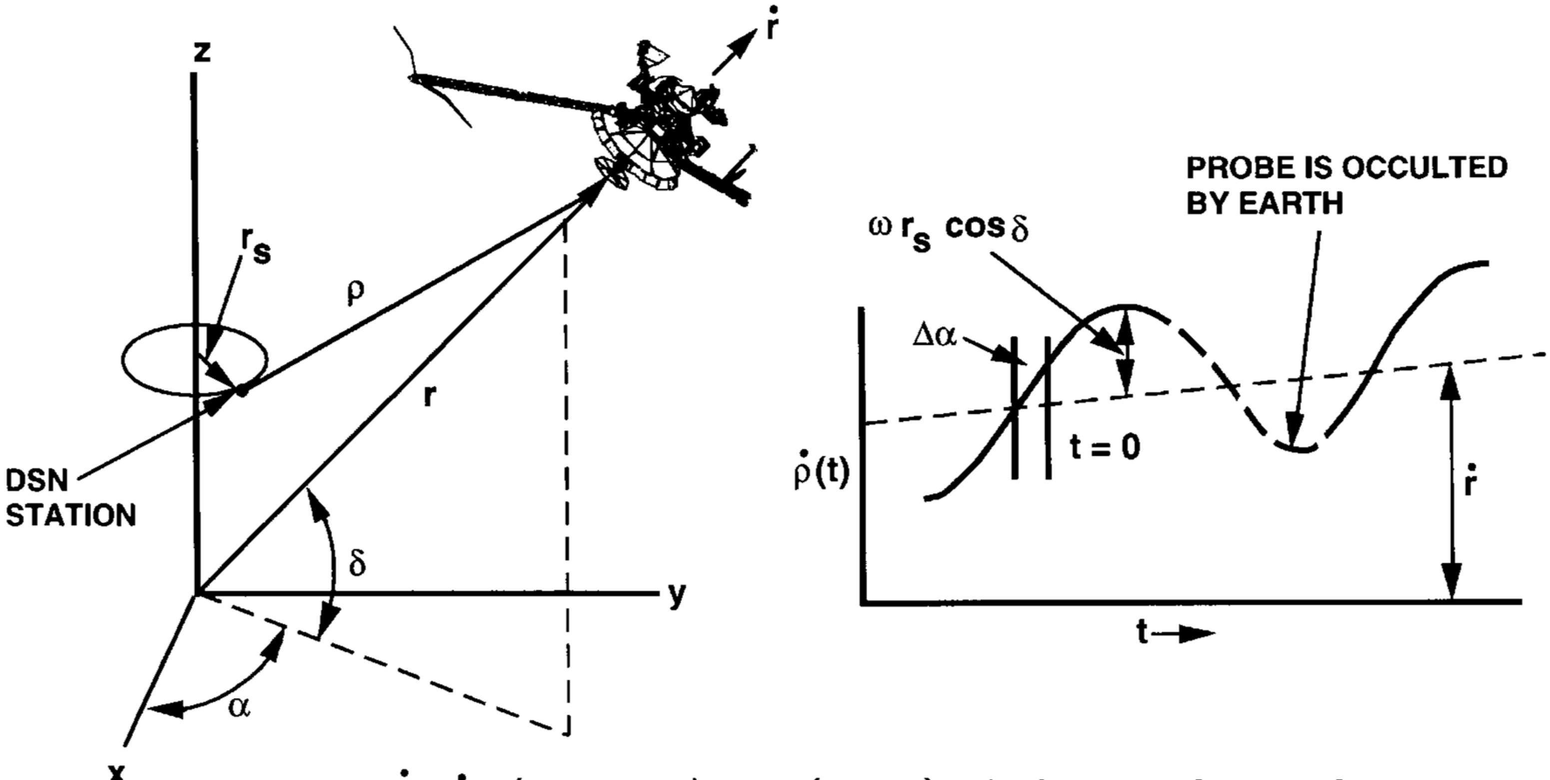
Navigation Measurements – Overview

- 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 measure-ments, 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



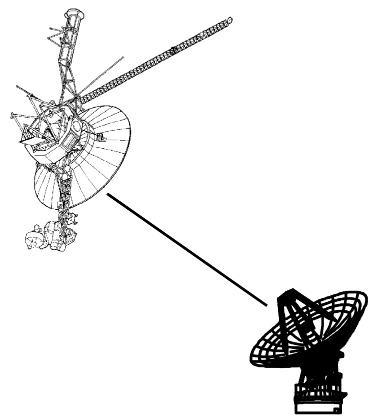
$$\dot{\rho} = \dot{r} + (r_s \omega \cos\delta) \sin \omega (t - t_m) + \text{OBSERVATION ERROR}$$

WHERE t_m IS THE TIME OF MERIDIAN CROSSING

Single-Station OD Capabilities

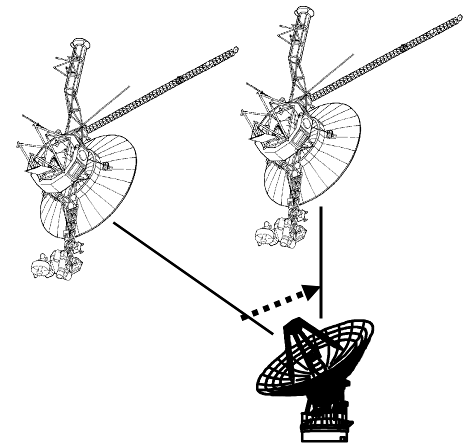
- Characteristics of Single-Station Doppler and Range Orbit Determination Capabilities
  - Radial velocity derived from mean trend in Doppler data
  - Radial position derived from mean trend in range data (or inferred from processing of Doppler data)
  - Declination derived principally from amplitude 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



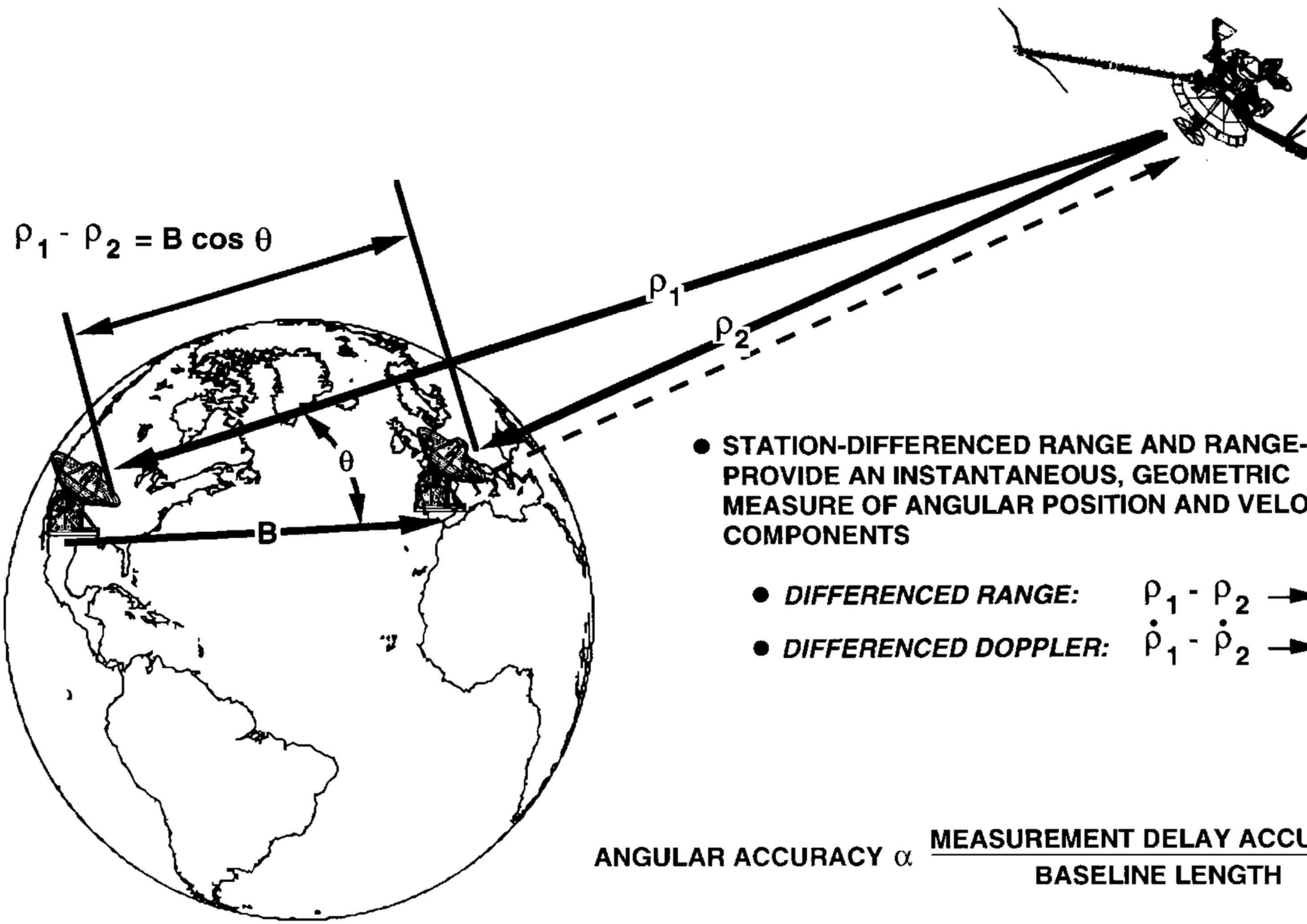
- Doppler
  - Measurements are comparisons of transmitted frequency (from ground station or spacecraft) with received frequency on ground; typical frequencies are at S-band (2 GHz),X-band (7-8 GHz), new Ka-band (33 Ghz)
  - Useful for all mission phases
  - Highly reliable; used in all interplanetary missions to date
  - Done by counting cycles at a DSN station…

- Range
  - Measurements are typically two-way light time for radio signal to propagate between ground stations and s/c; 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

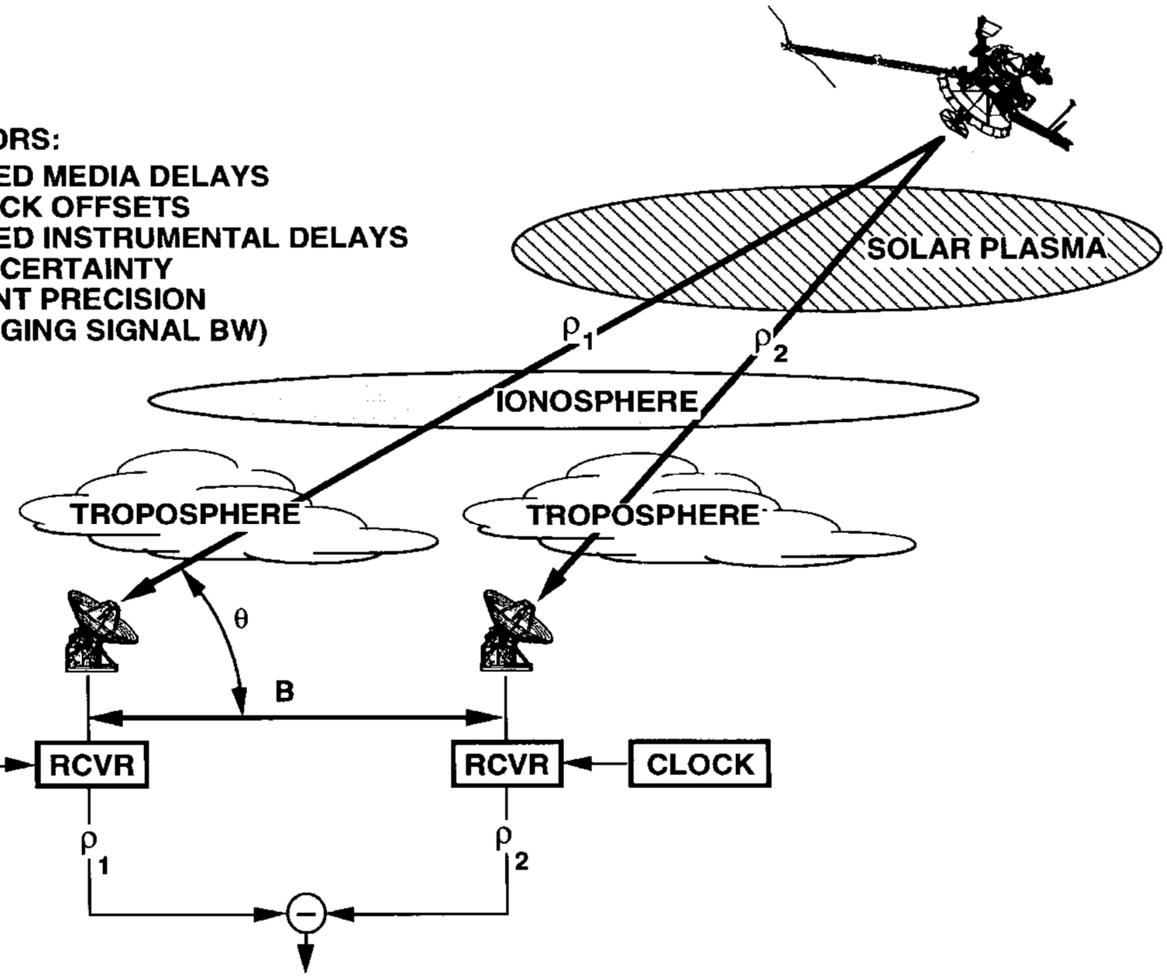


- STATION-DIFFERENCED RANGE AND RANGE-RATE PROVIDE AN INSTANTANEOUS, GEOMETRIC MEASURE OF ANGULAR POSITION AND VELOCITY COMPONENTS
  - *DIFFERENCED RANGE:* $\rho_1 - \rho_2 \rightarrow \theta$
  - *DIFFERENCED DOPPLER:* $\dot{\rho}_1 - \dot{\rho}_2 \rightarrow \dot{\theta}$

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

Differenced-Range Measurement Errors

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



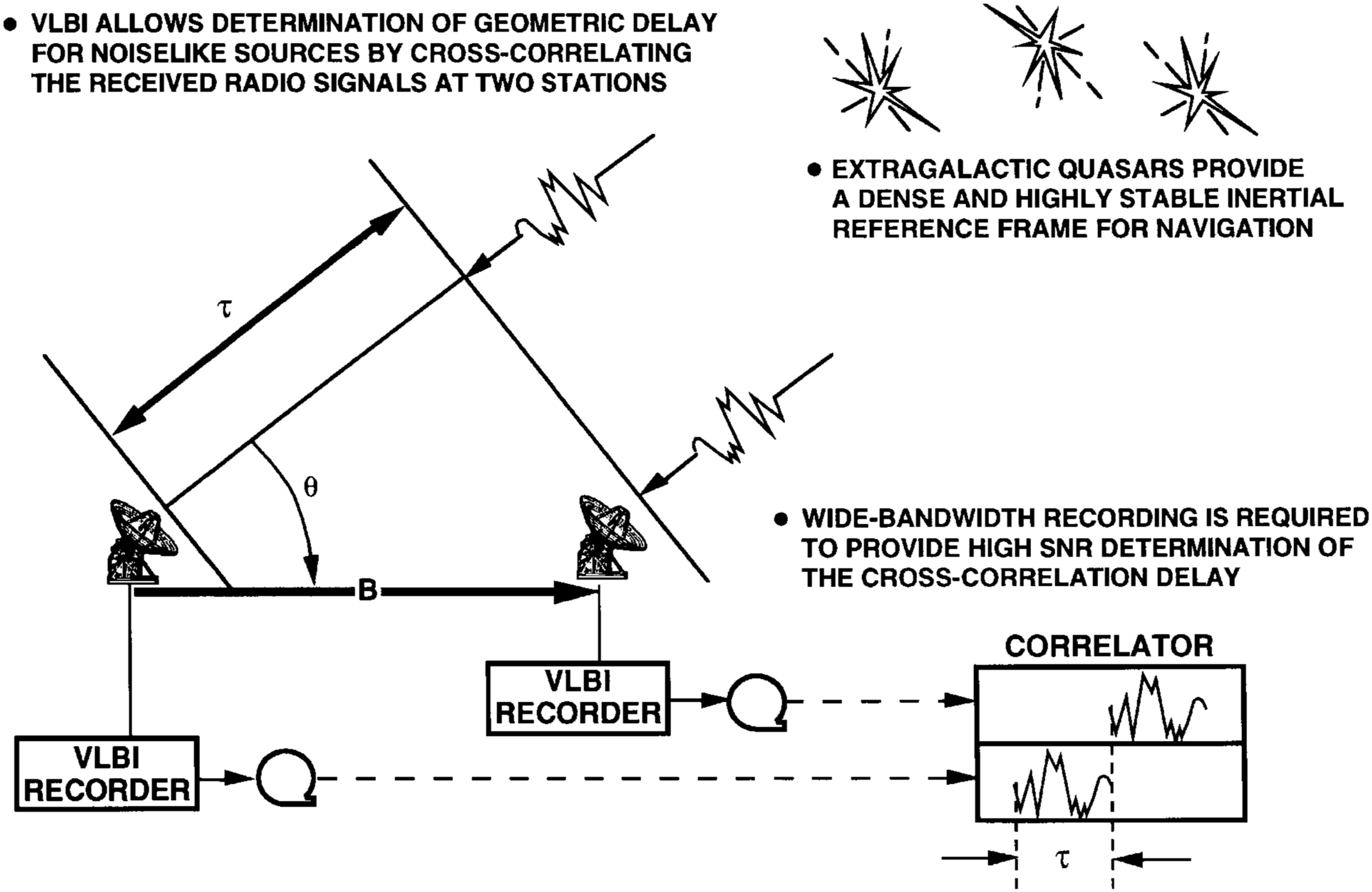
$$\rho_1 - \rho_2 = B\cos\theta + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + \text{NOISE}$$

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

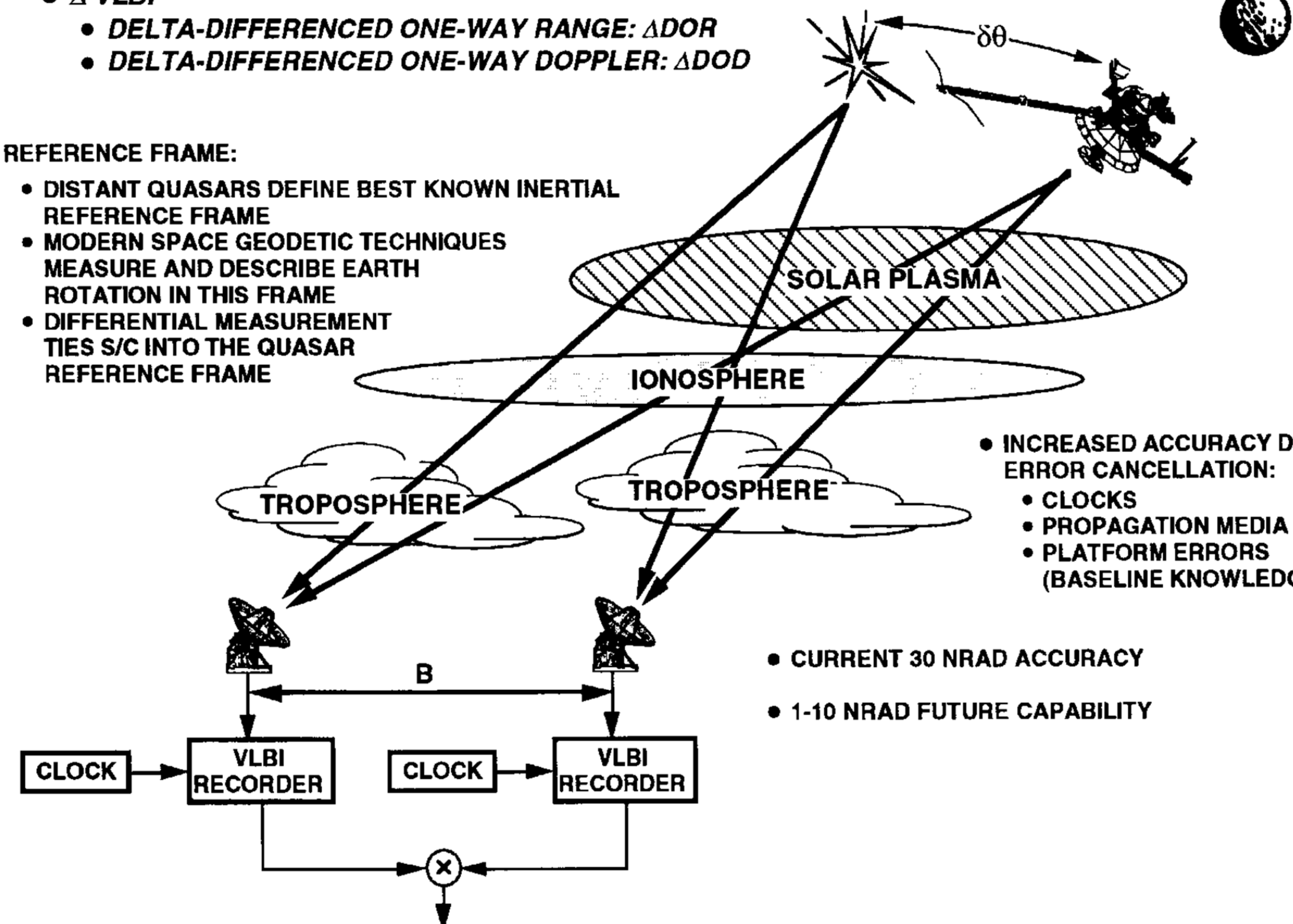
- WIDE-BANDWIDTH RECORDING IS REQUIRED TO PROVIDE HIGH SNR DETERMINATION OF THE CROSS-CORRELATION DELAY



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

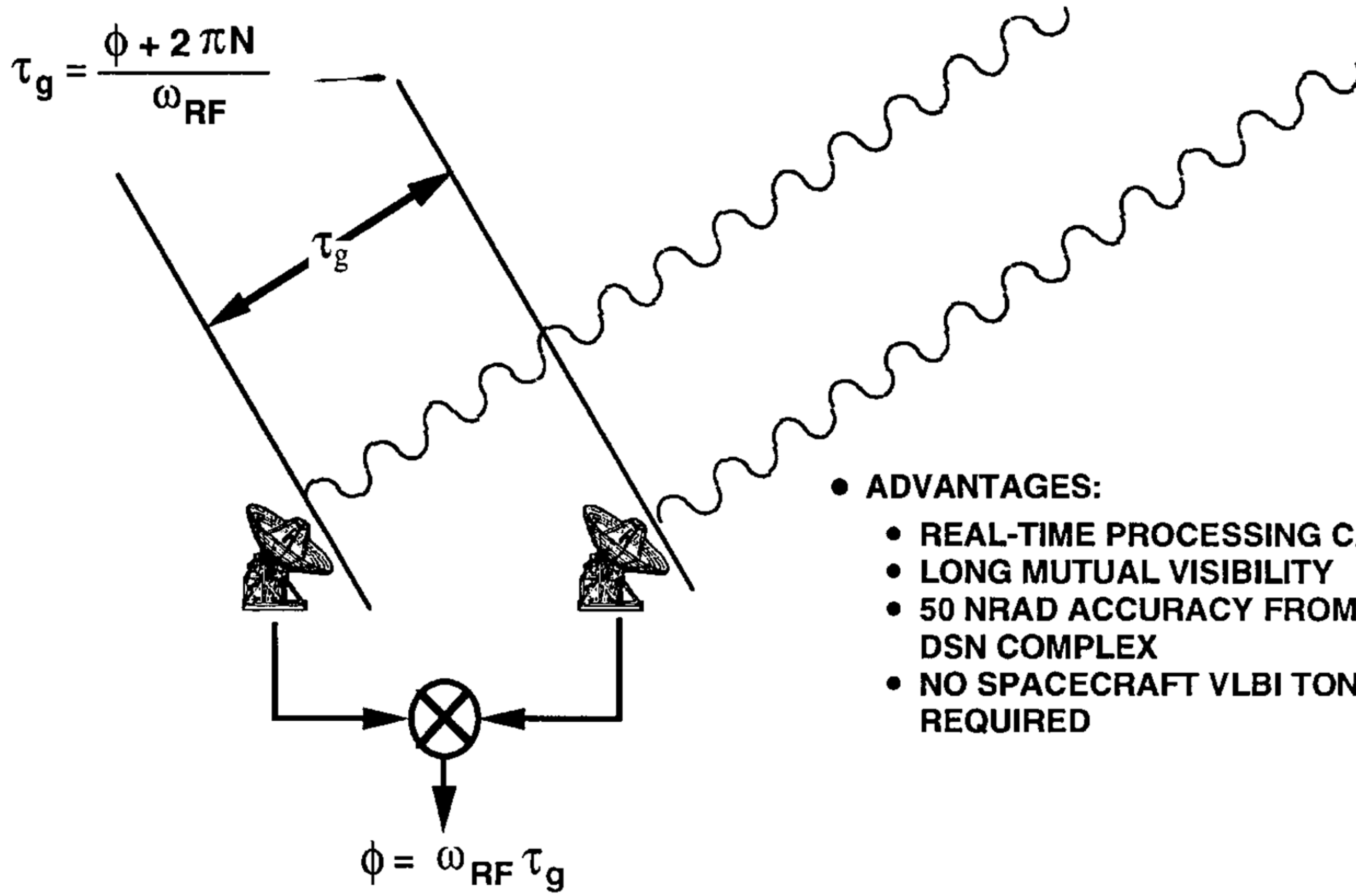
- 1-10 NRAD FUTURE CAPABILITY

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

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

Connected Element Interferometry

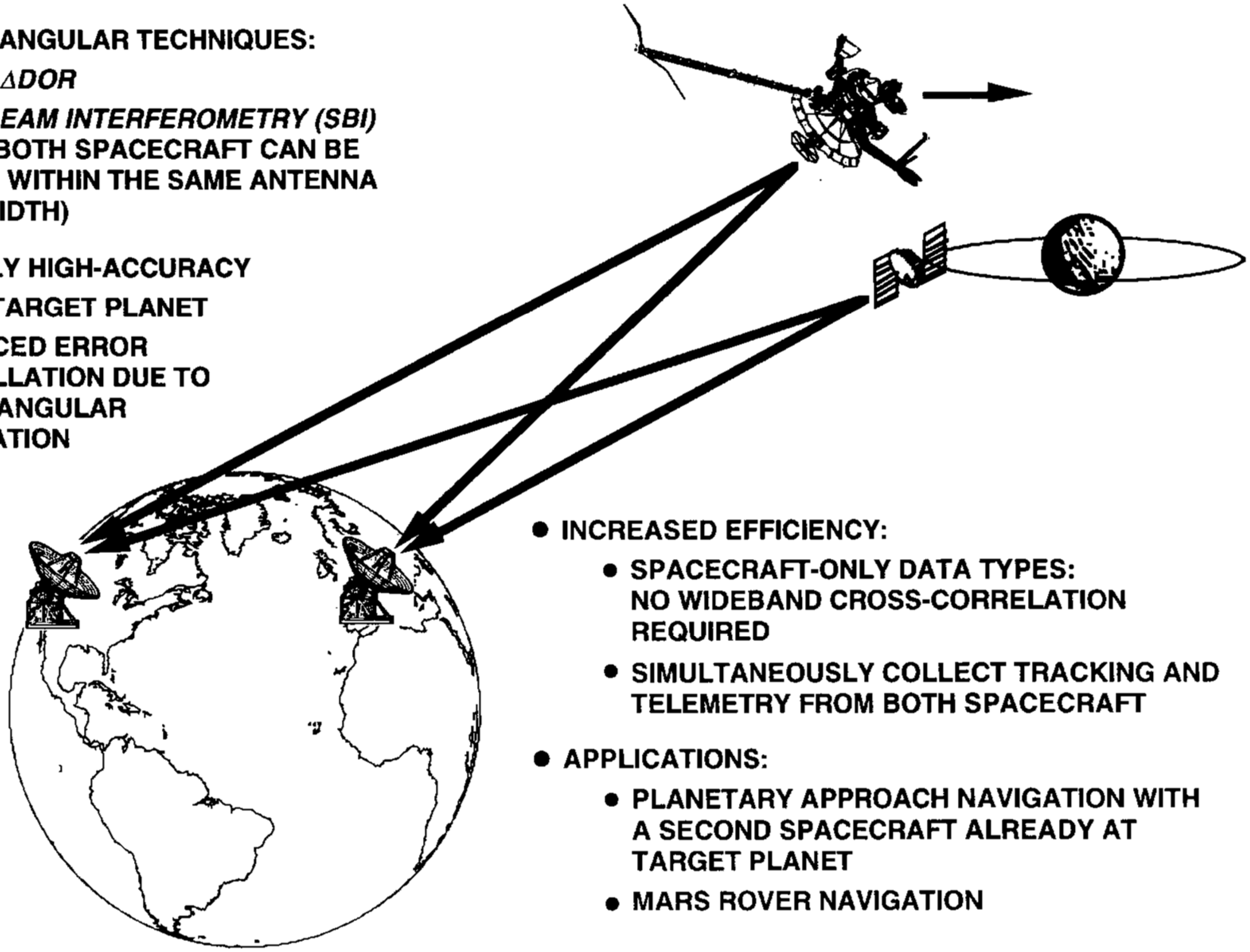
- *CONNECTED ELEMENT INTERFEROMETRY (CEI):*
  - ON SHORT BASELINES, THE INTERFEROMETRIC PHASE OBSERVABLE CAN BE USED DIRECTLY TO OBTAIN AN EXTREMELY PRECISE MEASURE OF GEOMETRIC DELAY



- 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

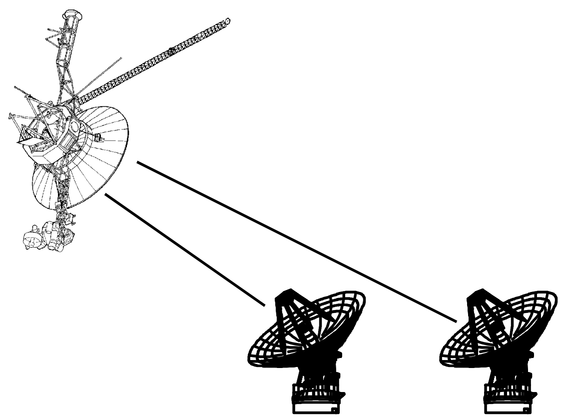
- MULTI-S/C ANGULAR TECHNIQUES:
  - *S/C-S/C ΔDOR*
  - *SAME BEAM INTERFEROMETRY (SBI)* (WHEN BOTH SPACECRAFT CAN BE VIEWED WITHIN THE SAME ANTENNA BEAMWIDTH)
- EXTREMELY HIGH-ACCURACY
  - TIE TO TARGET PLANET
  - ENHANCED ERROR CANCELLATION DUE TO SMALL ANGULAR SEPARATION

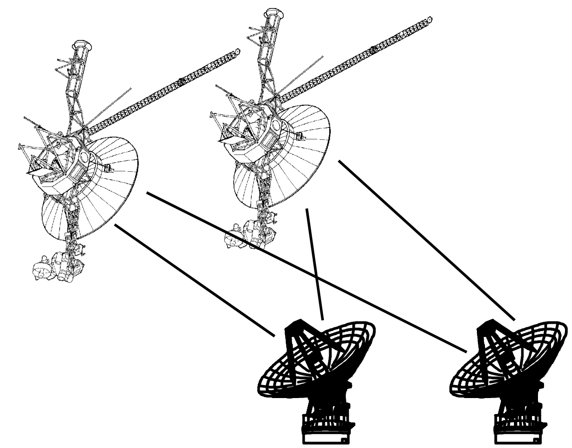


- INCREASED EFFICIENCY:
  - SPACECRAFT-ONLY DATA TYPES: NO WIDEBAND CROSS-CORRELATION REQUIRED
  - SIMULTANEOUSLY COLLECT TRACKING AND TELEMETRY FROM BOTH SPACECRAFT
- APPLICATIONS:
  - PLANETARY APPROACH NAVIGATION WITH A SECOND SPACECRAFT ALREADY AT TARGET PLANET
  - MARS ROVER NAVIGATION

Quasi-Interferometric Data Types

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





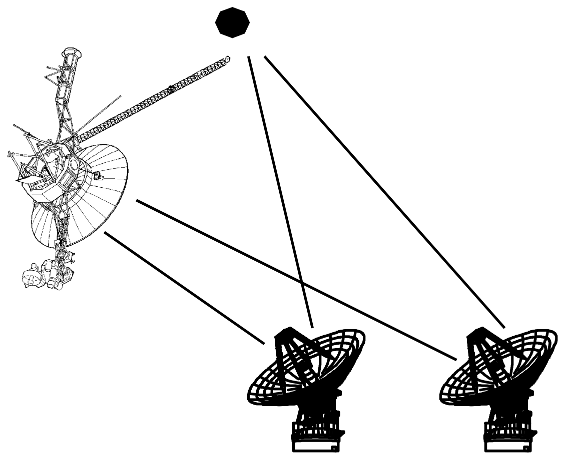
- Differenced Doppler
  - Measurements are difference in Doppler measurements at two different stations
  - Most useful during planetary approach and for planetary orbiters
  - Used in Magellan and Galileo missions

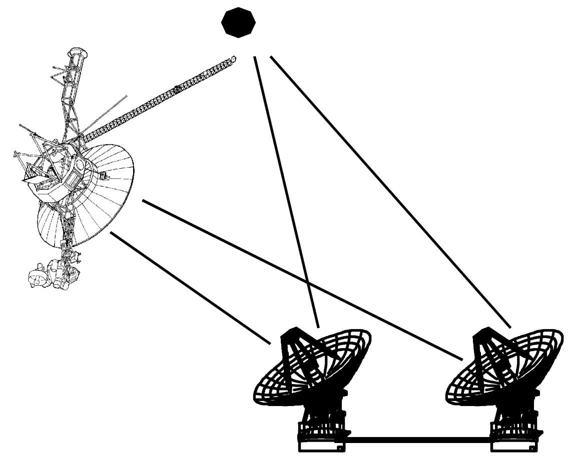
- Differenced Range
  - Measurements are difference in arrival times of spacecraft downlink signal at two different stations
  - Most useful during planetary approach and for outer planet orbiters
  - Used in Voyager mission

- Spacecraft-Spacecraft DDOR
  - "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 & second is nearing that planet
  - Applications are planetary approach navigation and planetary rover navigation

Radio-Interferometric Data Types

Radio Metric Measurements -- Interferometric Data Types

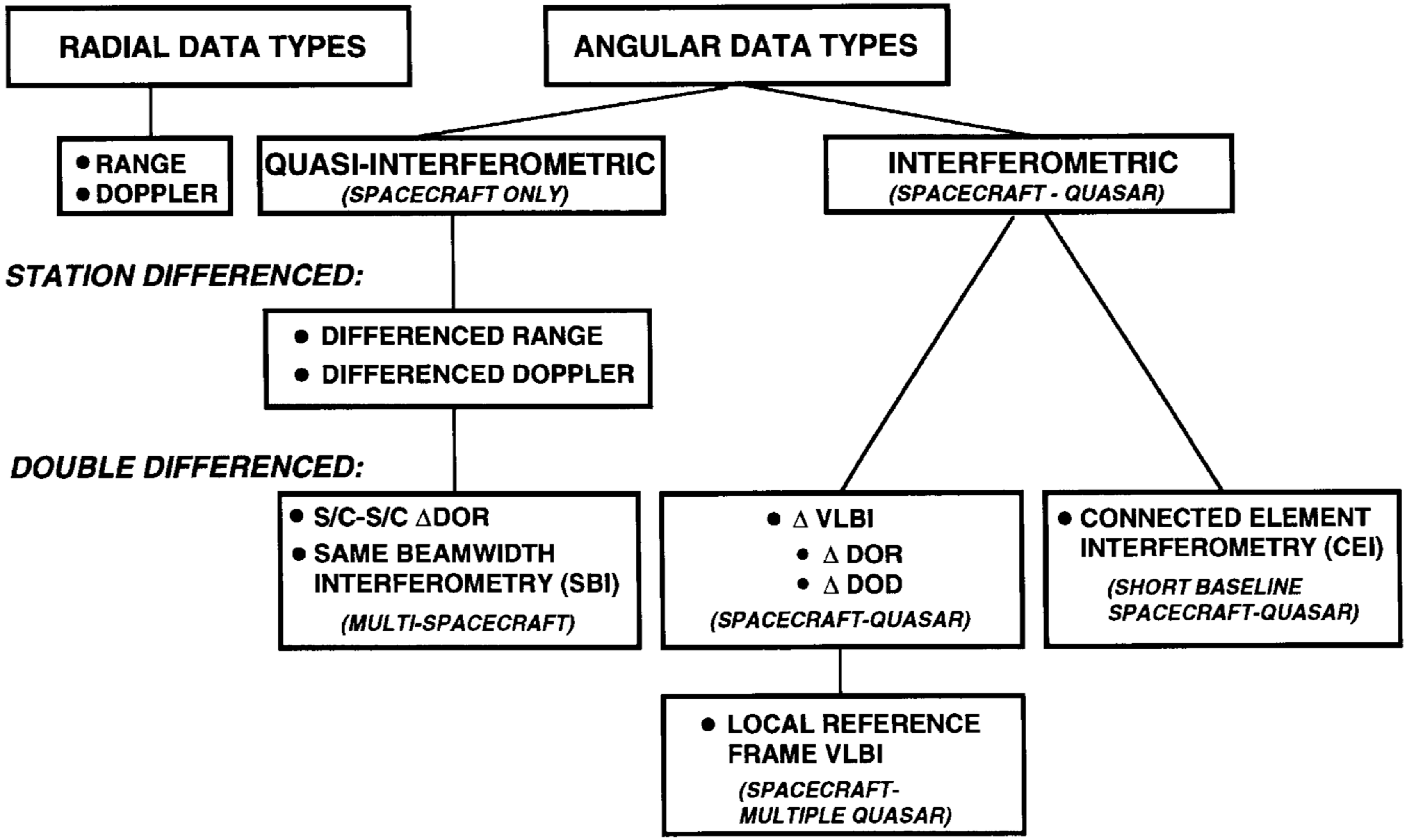




- Spacecraft-Quasar DDOR
  - Similar to Spacecraft-Spacecraft DDOR, with second spacecraft signal replaced with natural radio source such as quasar
  - Useful for planetary approach if no other spacecraft are nearby in sky
  - Used on Voyager, Ulysses, Magellan, Mars Observer, and Galileo

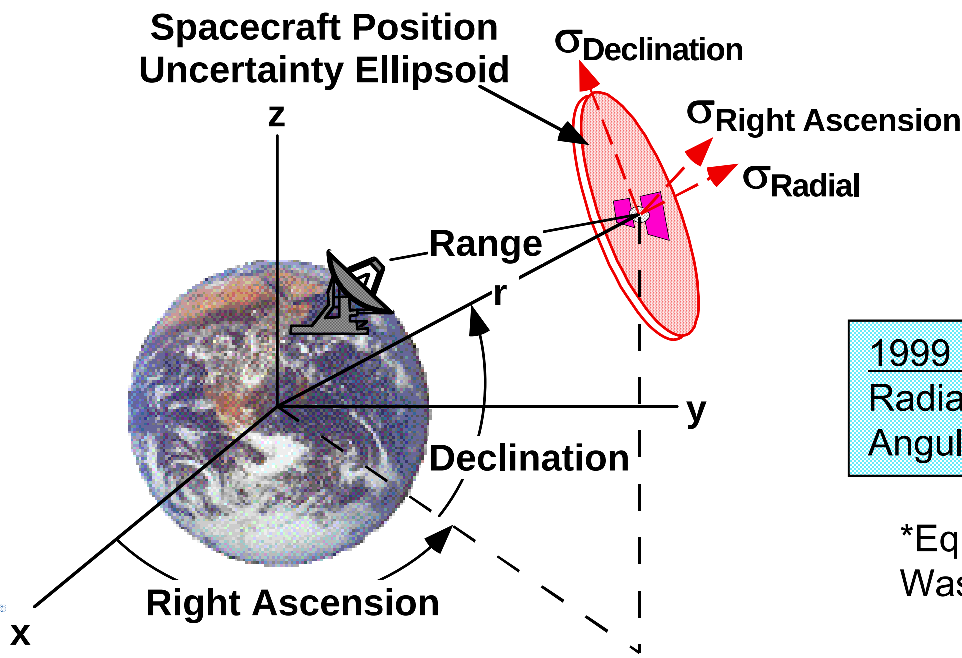
- Connected Element Interferometry
  - Uses doubly-differenced phase delay observable instead of group delay observable
  - Correlation can be performed in real-time
  - Applications are planetary approach navigation and interplanetary cruise navigation

Earth-Based Radio Tracking Family Tree



Radio Metric Orbit Determination Accuracy

- For most interplanetary missions, s/c 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: DDOR and NST data can directly measure these otherwise weaker angular components with varying accuracies

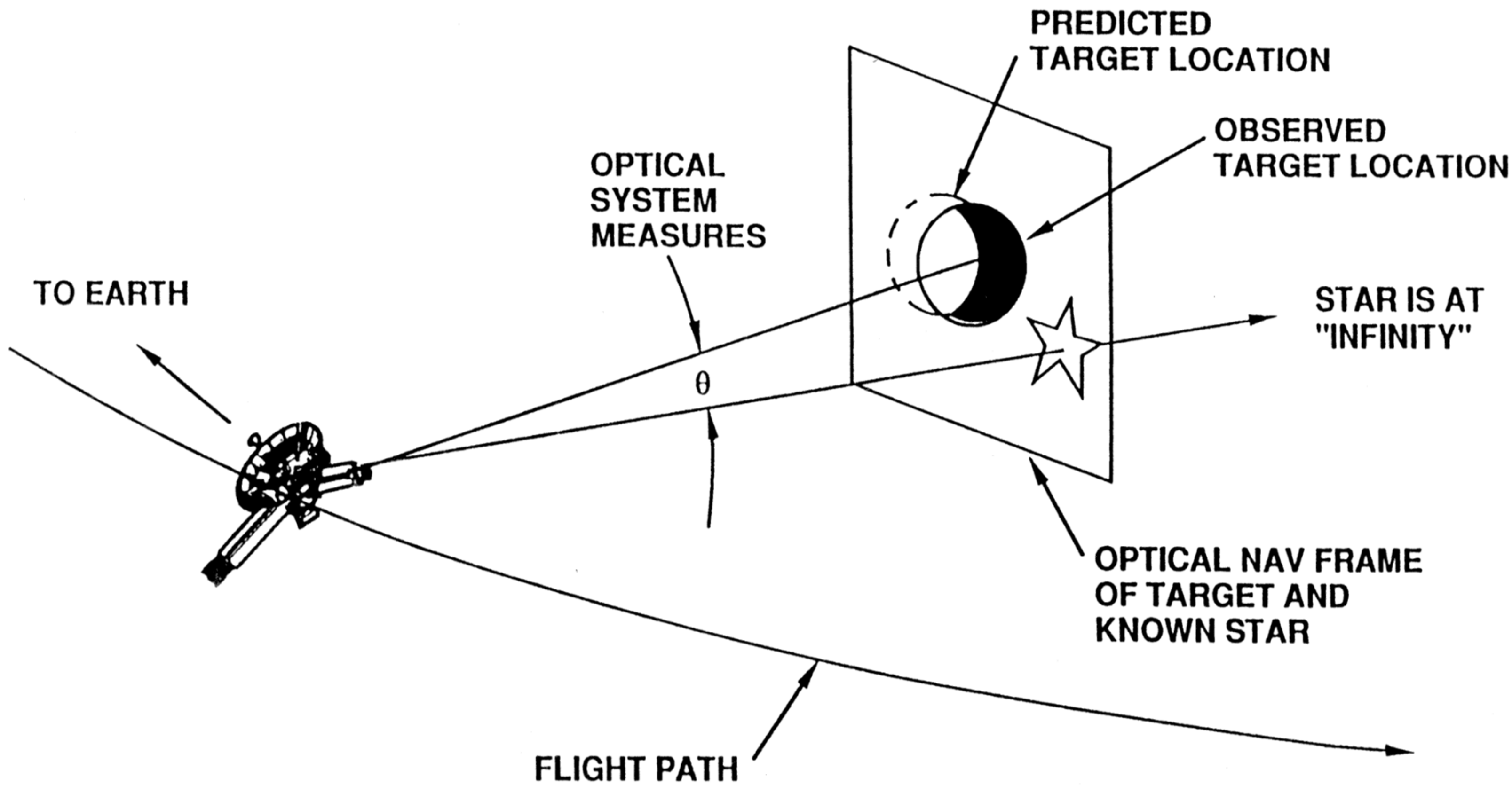
1999 Capability	Position	Velocity
Radial Error	2 m	0.1 mm/s
Angular Error (at 1 AU)	3 km*	0.1 m/s

*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 & 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

Impact of Non-gravitational Accelerations

Non-gravitational Accelerations – Impact on Navigation Performance

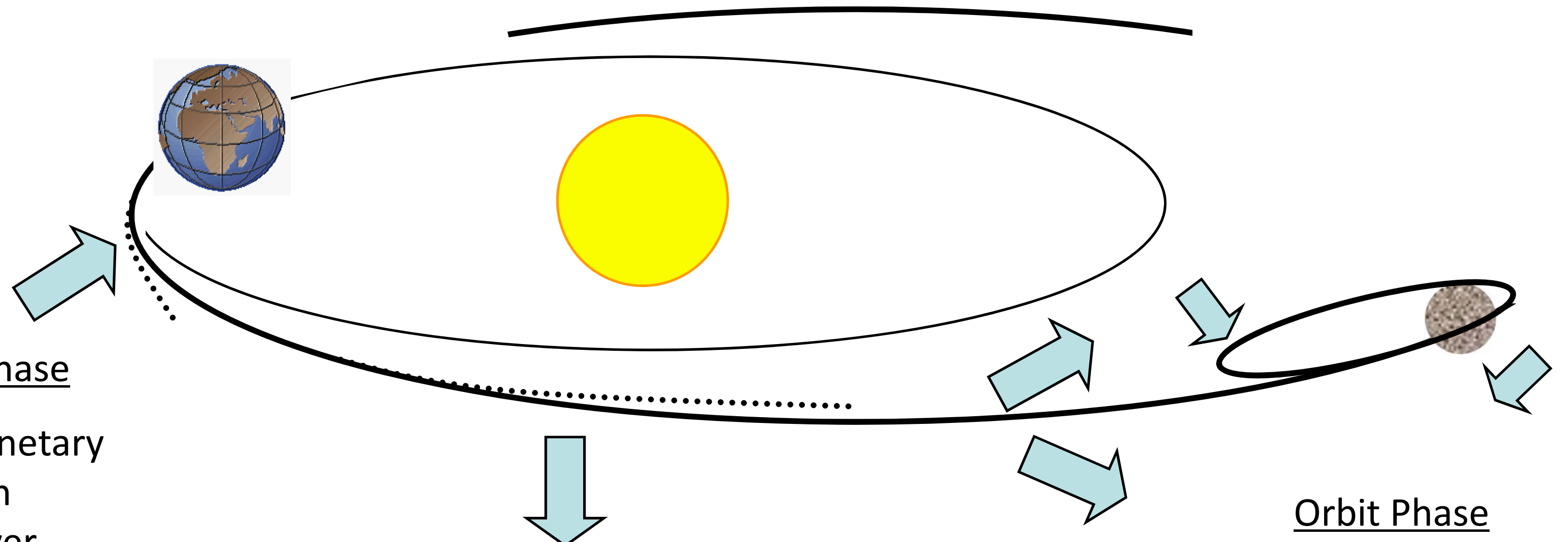
- Un-modeled non-gravitational accelerations can significantly affect spacecraft trajectories
  - For example, acceleration of 10^{-10} km/s^2 can shift trajectory by
    - 0.37 km in 1 day
    - 37 km in 10 days
    - 3700 km in 100 days
- Un-modeled non-gravitational accelerations can also significantly degrade spacecraft trajectory estimates
  - Failure to model non-gravitational 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)

- 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

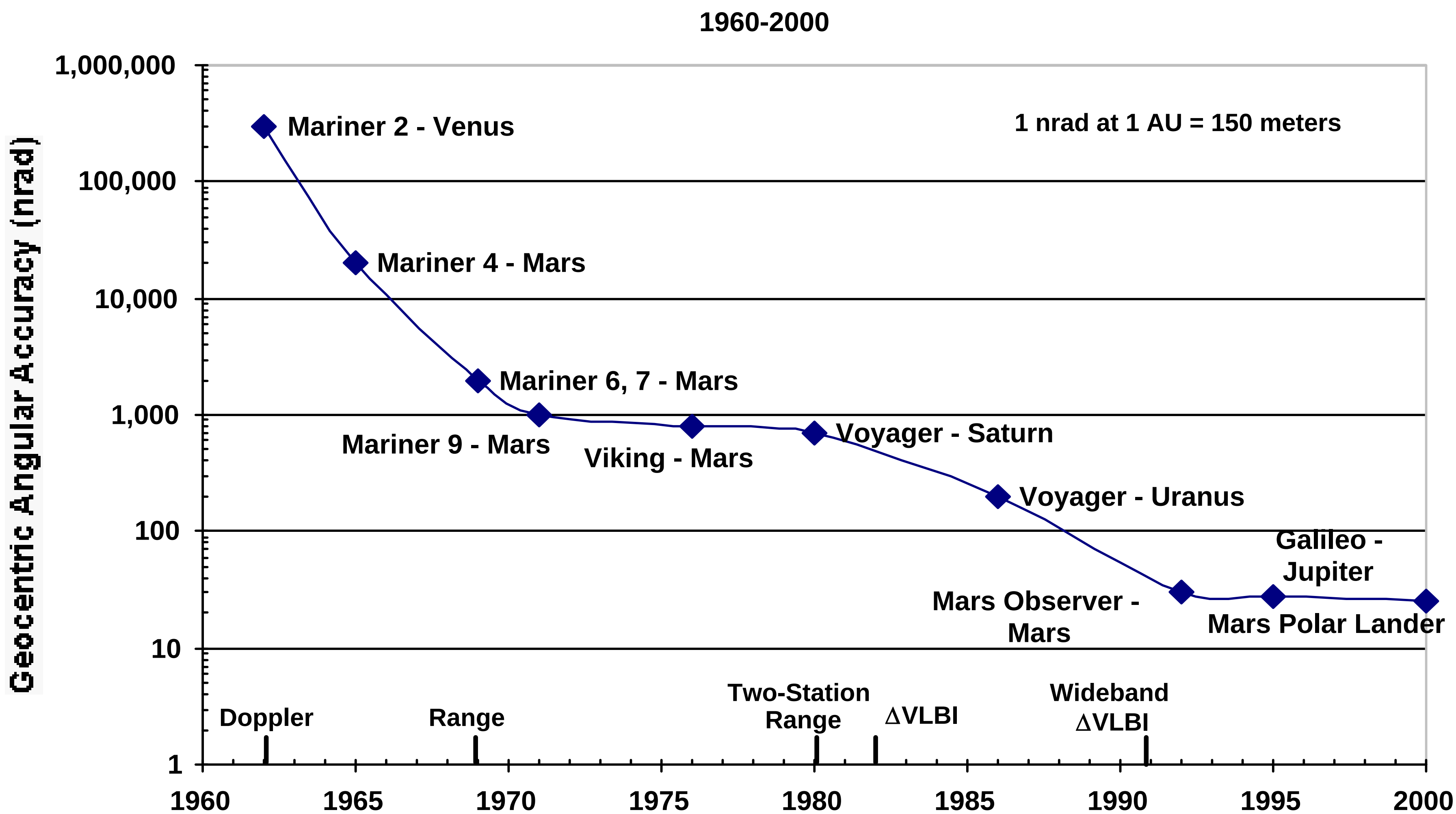
- Approach Guidance Maneuvers

Orbit Phase

- Orbit Insertion Maneuver

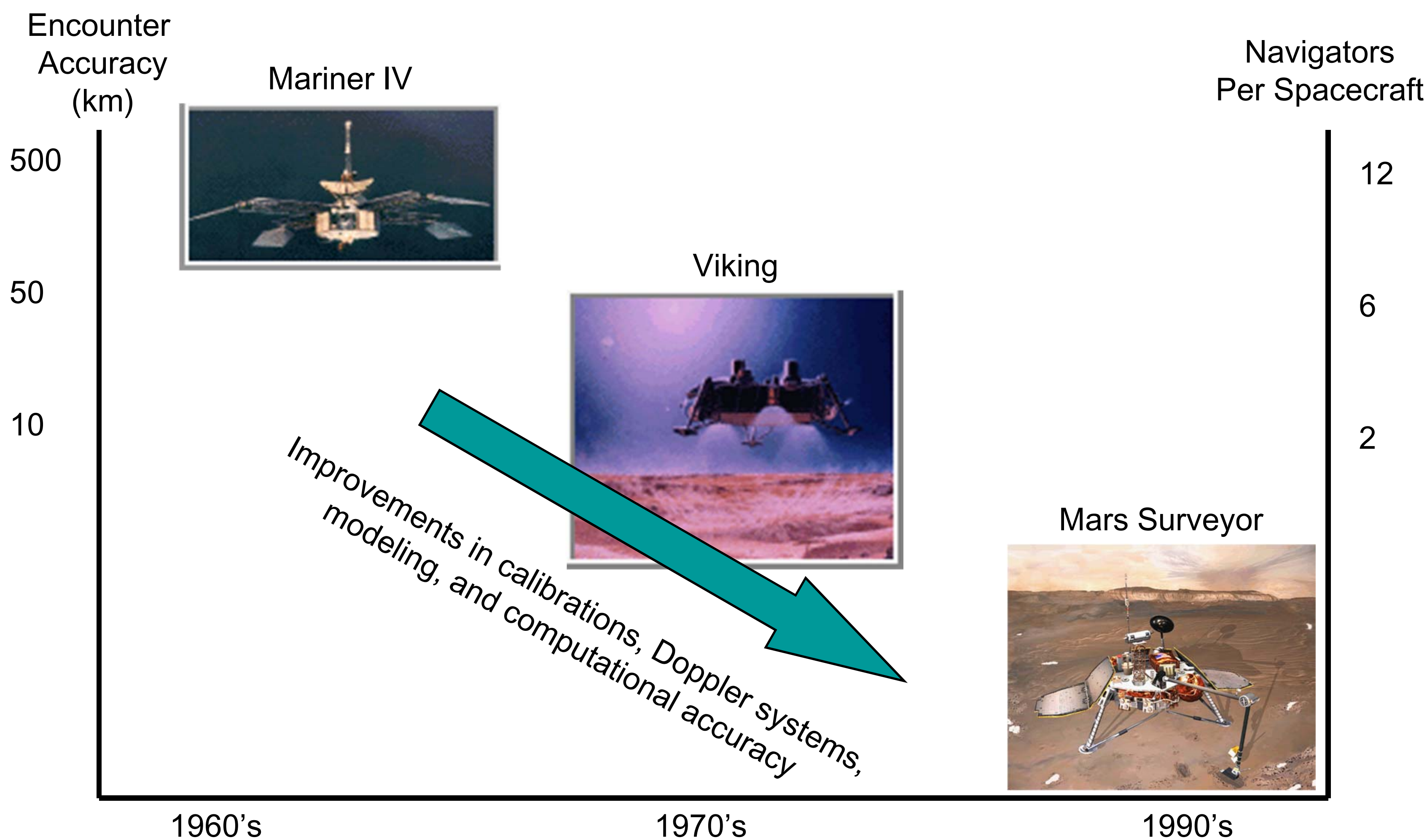
In typical interplanetary trajectory, depicted here, propulsive maneuvers are required to correct injection errors, make small orbit changes at mid-course and final approach, and achieve final trajectory at planetary target

Evolution of Deep Space Navigation System



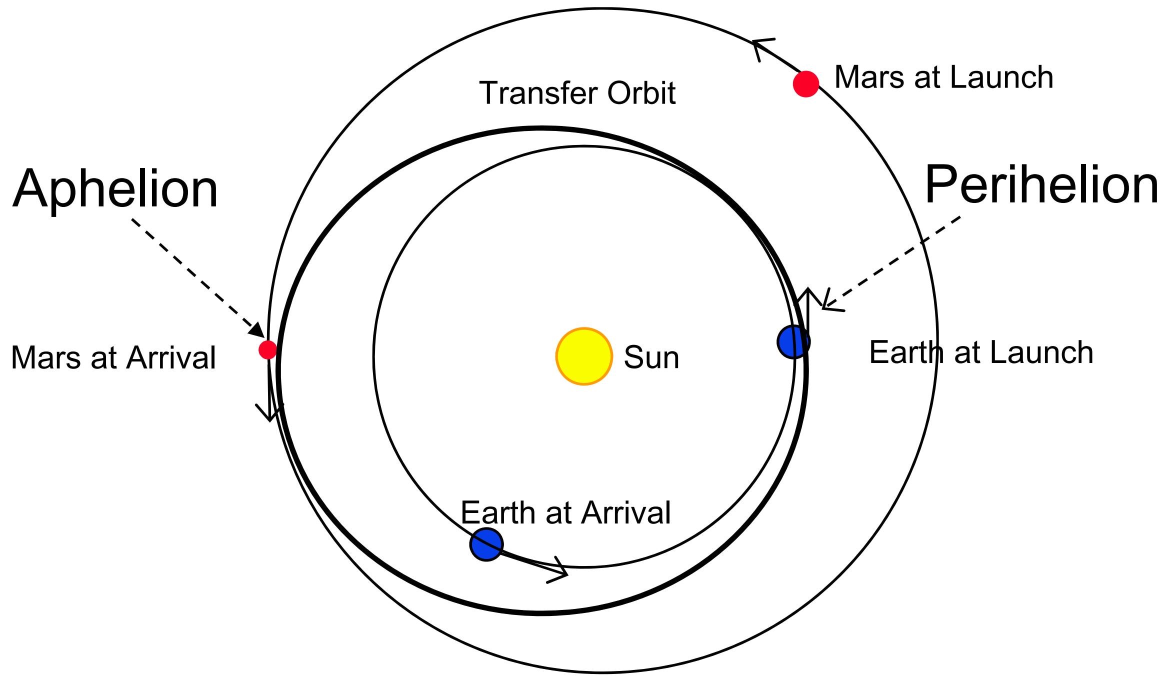
Deep Space Navigation System: Evolution of DSN Navigation System Accuracy

Benefits of Improved Radio Navigation



Benefits of Improved Radio Navigation Accuracy to Mars Missions

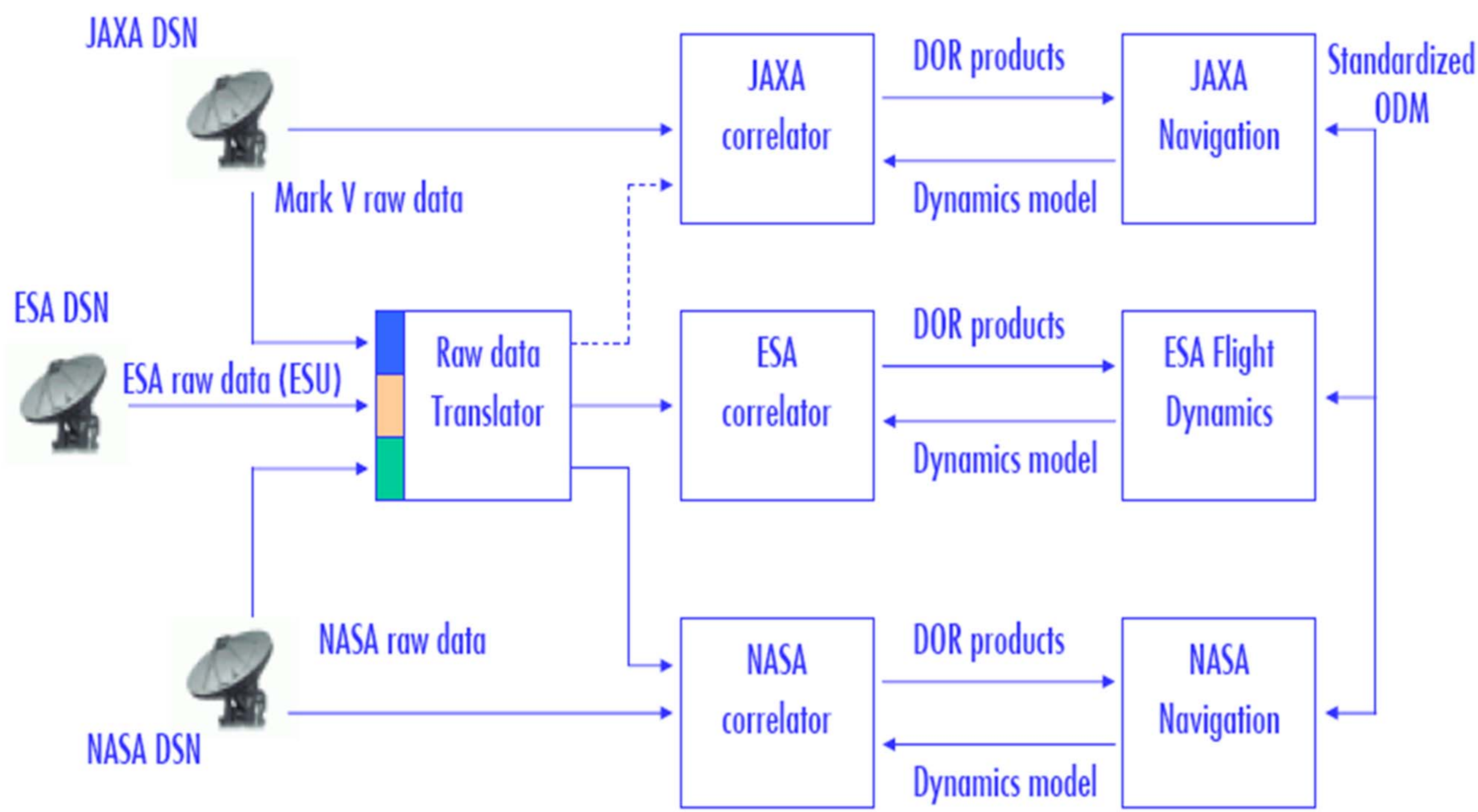
Example Trajectory: Earth-Mars



- For many interplanetary missions, the trajectory plan has three phases:
  1. Escape the Earth's gravitational influence
  2. Complete an interplanetary transfer orbit
  3. Enter a planned orbit at the target body, or land on the target body

Note: Typical Earth-Mars distances vary from ~0.5 to 2.5 AU, or 75 to 375 million km

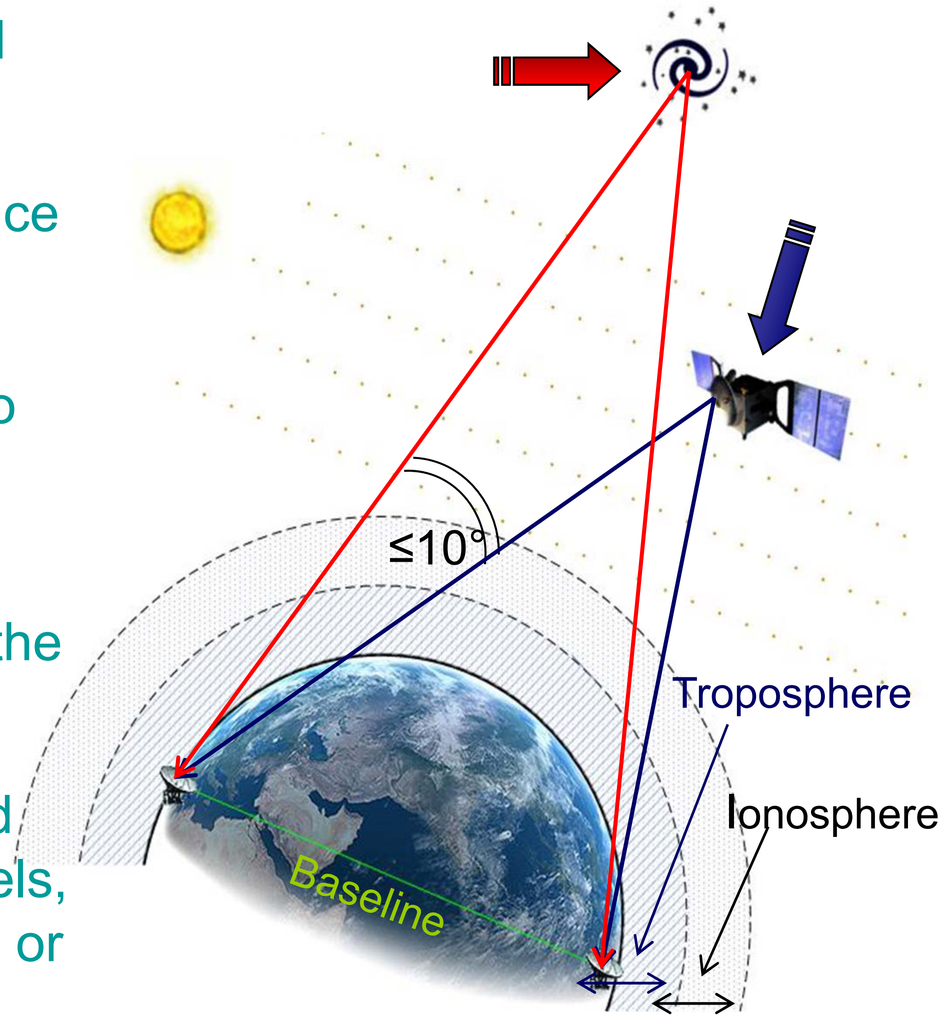
NASA/JPL, ESA, and JAXA cross support



BUCK-UP SLIDES

ΔDOR definitions (1)

- .ΔDOR stands for Delta-Differential One Way Ranging
- DOR is the measure of the difference in signal arrival time between two stations. The observable is an uncalibrated delay between the two antennas
- "Delta" is respect to a simple DOR, and refers to quasar calibration of the S/C DOR
- Since the quasar signal is recorded on the same BW of the S/C channels, ideally any errors which are station or path dependent will cancel



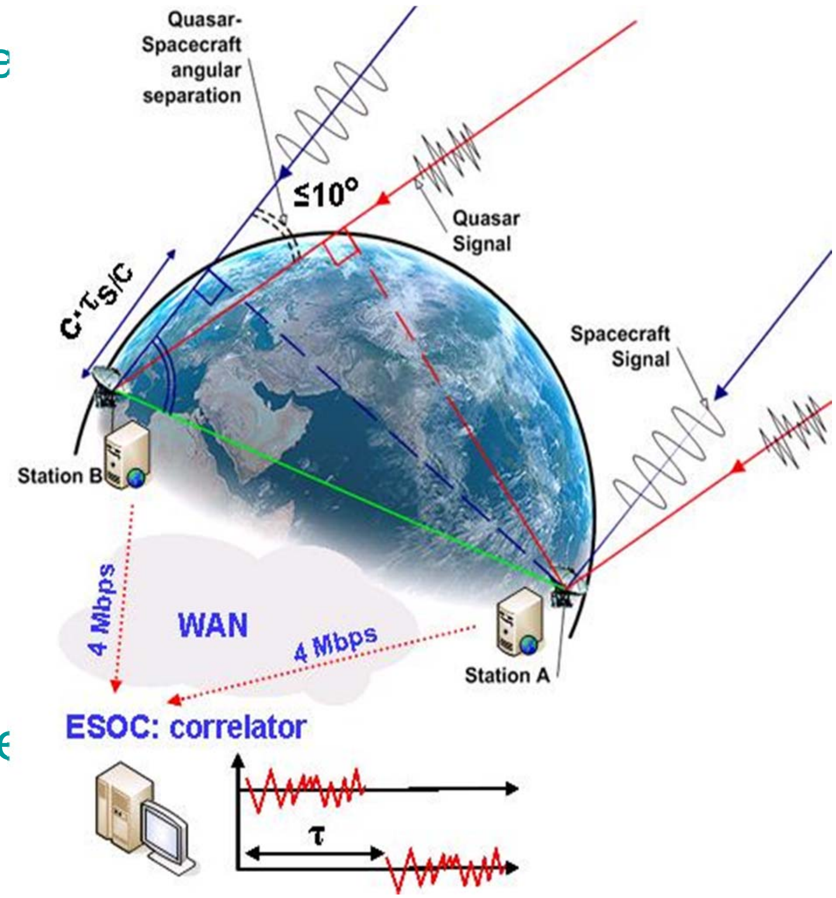
ΔDOR definitions (2)

- The extent to which these error source cancel depends on the angular separation of the two sources being observed. The maximum angular distance between S/C and Quasar should not exceed 10 deg.

- Thus, one is able to evaluate a potentially error-free relative station delay, which leads to an accurate determination of the S/C position in the plane of the sky

- The measurement accuracy is given by:

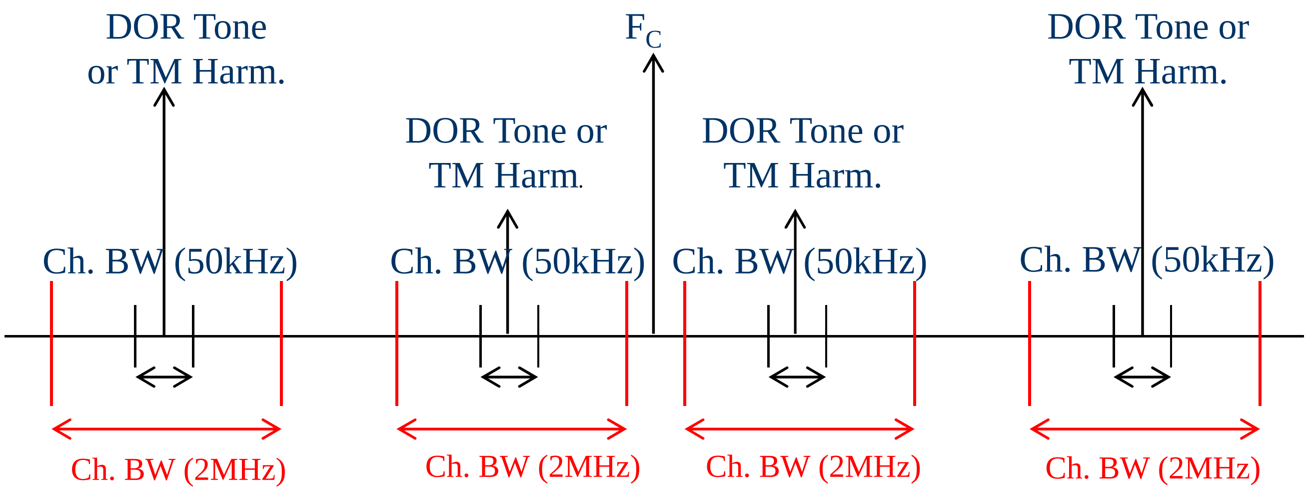
$$\frac{\partial \vartheta}{\partial \tau} = -\frac{c}{B \cos \vartheta}$$



Longer baselines, better accuracies

ΔDOR definitions (3)

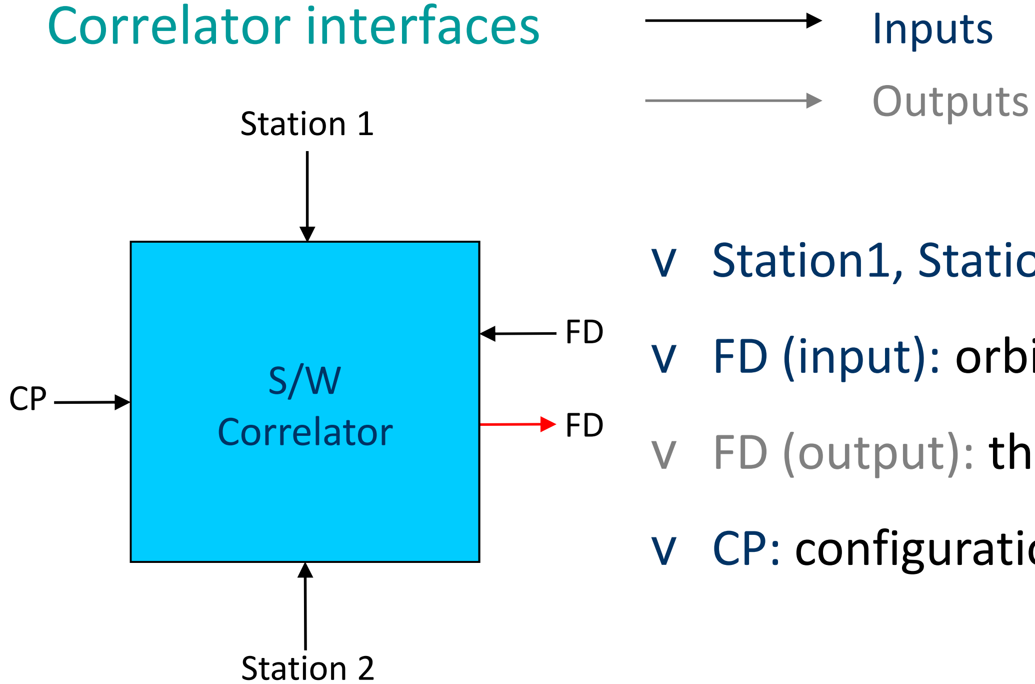
- Observation Sequence: S/C – Quasar – S/C (or Q-S-Q)



- S/C Signal: telemetry harmonic (or DOR tone)
- Quasar Signal: white noise (embedded in the receiver noise)

ΔDOR Correlator (1) I/F definitions

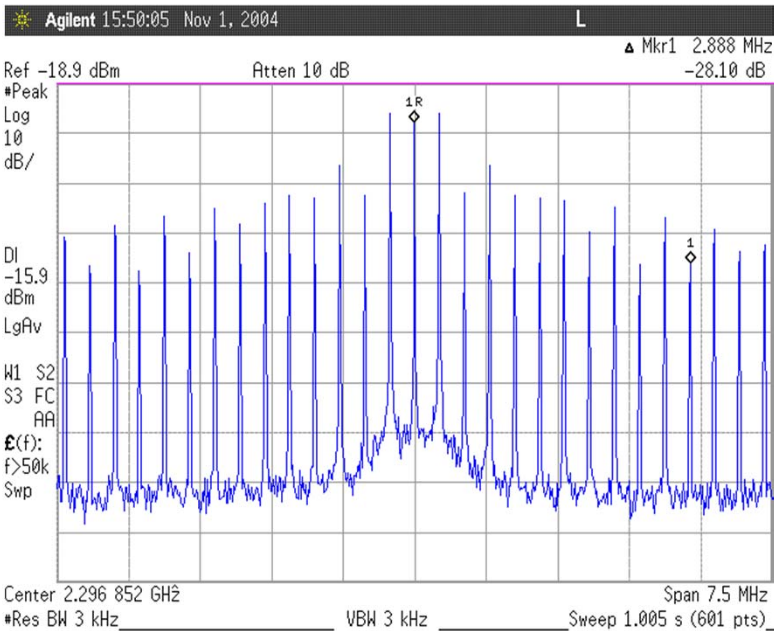
- Correlator interfaces



- Station1, Station2: open loop data
- FD (input): orbital data to help the correlation
- FD (output): the final product of the correlation
- CP: configuration parameters

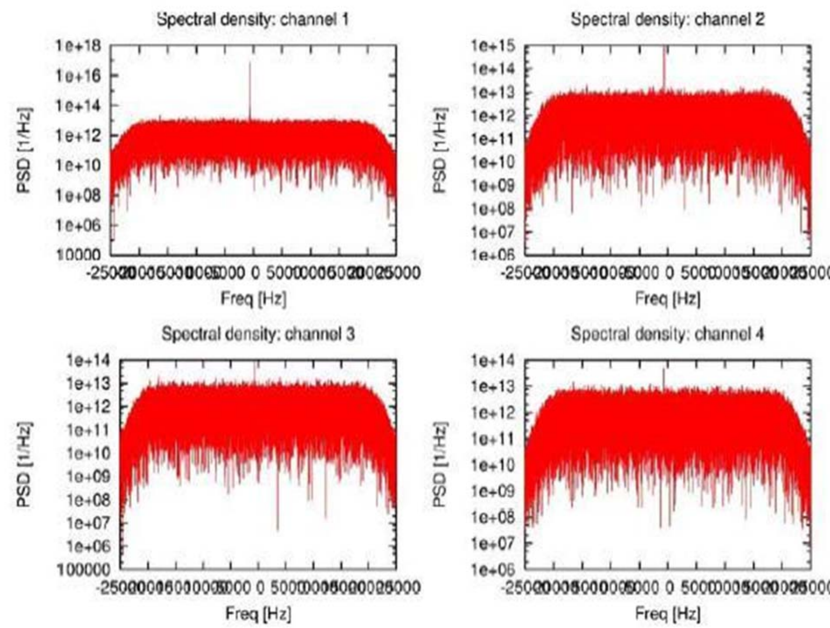
- S/C signal correlation
  - Set of TM harmonics: signal characteristic permits phase extraction
- Quasar signal correlation
  - Noise-like signal totally embedded in receiver noise: signal characteristic forces to go for a direct correlation method

ΔDOR correlator (2) S/C signal structure



Spectrum of the TM harmonics (up to the 14th) of the Rosetta transponder

Spectra (over 1 second data) of the four 50kHz channels recorded during one of the passes



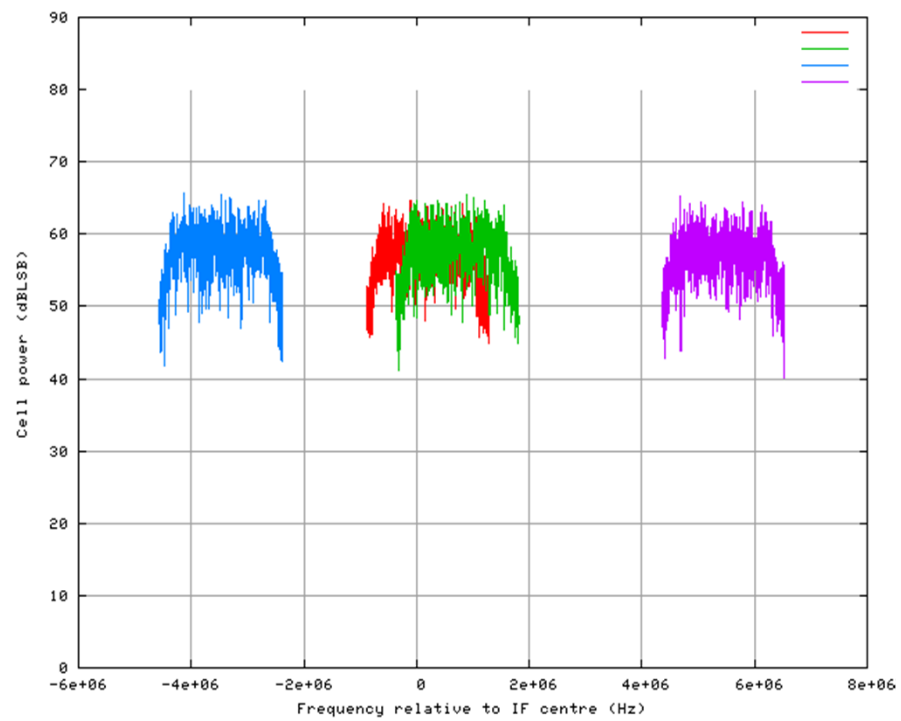
ΔDOR correlator (3) S/C signal correlation

- Phase extraction by means of a S/W frequency estimator on the carrier and the lowest order TM even harmonic (highest in S/N)
- Drive the phase extraction of all other tones with the model (properly Doppler-scaled) built on the lowest order TM harmonic
- Multiplication of the extracted phasor with a phasor computed using the FD model
  - At this point, we have the phase sequences of each TM harmonic at each Station, sufficiently corrected for phase uncertainties
- Correlation of the phase of each channel of Station 1 with the phase of the corresponding channel of Station 2
- The correlation result as such is “modulo 2π” ambiguous
- After an ambiguity resolution process a S/C DOR delay ($\tau_{S/C}$) is obtained

ΔDOR correlator (4) Quasar signal structure

- Quasar signal
  - Random noise-like signal
  - Quasar signal is totally embedded in antenna noise
  - Need for a wider channel BW to accumulate enough Signal-to-noise

Spectra (over 1 second data) of the four 2MHz channels recorded during one of the passes



ΔDOR correlator (5) Quasar signal correlation

- Each data stream (channel) from each station is delay- and Doppler-compensated (using the model provided by FD). The delay is mostly due to Earth rotation
- After delay- and Doppler- correction, each data stream of Station 1 will be correlated with the corresponding data stream of Station 2 for a range of delays (few μs) around the expected value (provided by FD)
- The analysis of the observed data is split in observation periods ("accumulation periods") of typically 1 s, in order to keep a tolerable level of error in Doppler compensation
- Correlation is performed for a suitable integration time (typically 10 min) in order to maximise the signal-to-noise ratio
- Delay resolution is improved by the use of available multi-band recordings (enlarging the total spanned bandwidth: "bandwidth synthesis")
- The result of the correlation is then added to the value given by FD model
- As a result, one obtains a Quasar DOR (τ_Q)

ΔDOR correlator (6) Correlator output

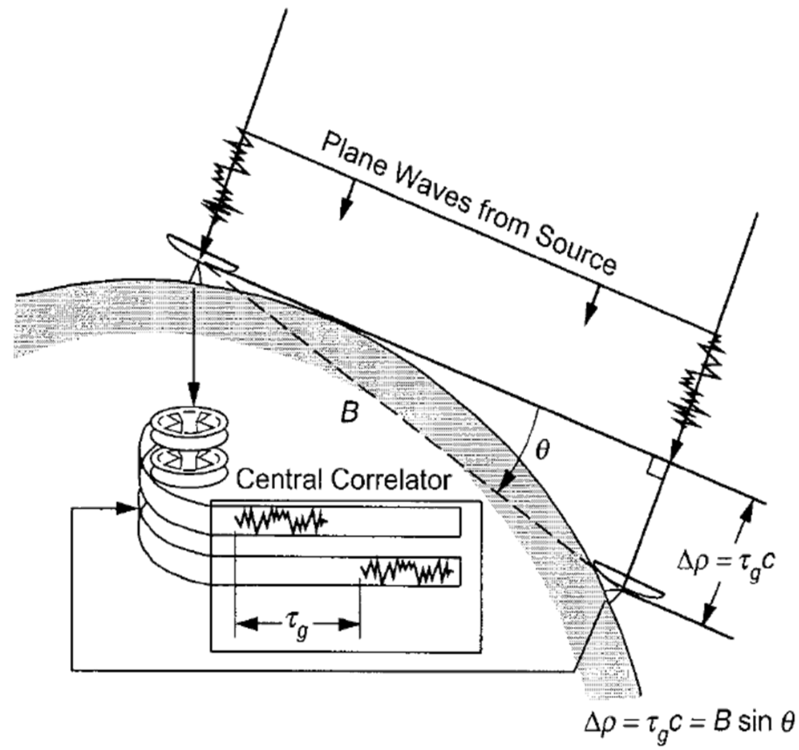
- The final output of the correlator is a file containing three DOR measurements (in the table only the most important parameters are reported).

RECORD NUMBER {12345}	
TT(1) = 0.1234567890123456D+NN	TIME TAG IN UTC = YYYY/MM/DD HH:MM:SS.SSS
OBS(1) = 0.1234567890123456D+NN	S/C DOR (NS) $\tau_{S/C}$
SOBS(1) = 0.1234567890123456D+00	DOR SIGMA (NS)
FREQ(1) = 0.1234567890123456D+NN	MEAN REC.FREQ.(MHZ)
RECORD NUMBER {12345}	
TT(1) = 0.1234567890123456D+NN	TIME TAG IN UTC = YYYY/MM/DD HH:MM:SS.SSS
OBS(1) = 0.1234567890123456D+NN	QUASAR DOR (NS) τ_Q
SOBS(1) = 0.1234567890123456D+00	DOR SIGMA (NS)
FREQ(1) = 0.1234567890123456D+NN	MEAN REC.FREQ.(MHZ)
RECORD NUMBER {12345}	
TT(1) = 0.1234567890123456D+NN	TIME TAG IN UTC = YYYY/MM/DD HH:MM:SS.SSS
OBS(1) = 0.1234567890123456D+NN	S/C DOR (NS) $\tau_{S/C}$
SOBS(1) = 0.1234567890123456D+00	DOR SIGMA (NS)
FREQ(1) = 0.1234567890123456D+NN	MEAN REC.FREQ.(MHZ)

Orbit determination

- To obtain a ΔDOR observation, the two S/C observations are linearly interpolated to the time of one Quasar observation. Direct differencing of the observations can then be made.
- The obtained time is used to correct FD estimation of the delay we are looking for.

- The corrected delay is then used to calculate the angle between the line orthogonal to the baseline and the S/C direction
- Results are then calibrated for media effects
- Overall accuracies are mainly driven by:
  - Maximum spanned BW
  - SNR of S/C and Quasar signals



Example of error budget

Main Parameters

B = Baseline	11621	km
Ch_bw = Channel Bandwidht (Quasar)	2.00E+06	Hz
Ch_bw = Channel Bandwidht (S/C)	5.00E+04	Hz
Theta = Angular dist. between S/C and EGRS	10	deg
eps_quas= quasar position uncertainty	1	nrad
eps_stn = Station Position uncertainty	2	cm
F = Reference Frequency	8.40E+09	Hz
gamma_q = Quasar Elevation	15	deg
m_TM = modulation index TM	1.25	rad
gamma_sc = S/C Elevation	12	deg
N_c = Number of Channels	4	
R1 = Antenna 1 Radius	17.5	m
R2 = Antenna 2 Radius	17.5	m
ro_z = Zenith Path Delay Uncertainty	5	cm
Rx S_No = Rx Signal to Noise	50	dBHz
Samp = Sampling Quasar data (1,2,4,8,16)	2	bits
Sc = Source Flux	0.7	Jy
SEP = Sun-Earth-Probe Angle	50	deg
Sub_freq = Subcarrier Frequency	2.62E+05	Hz
TM_deg = TM Harmonic Degree	20	
Tobs_q = Observation Time quasar	10	min
Tobs_sc = Observation Time S/C	6	min

	DELAYS using TM		
	Type	**Value (nsec)**	
	Clock Instability	0.000	Station
	Earth Orientation	0.052	Geodesy
	Instrumental Phase Ripple TM	0.053	S/C
	Ionosphere	0.006	Link
$\varepsilon_{\tau Q}$	Quasar observation accuracy	0.297	
	Quasar Position	0.039	Astronomy
$\varepsilon_{\tau S/C}$	S/C observation accuracy	0.401	
	Solar Plasma	0.000	Link
	Station Location	0.058	Geodes
	Troposphere	0.252	Link
	TOTAL (RMS)	**0.569**	

$$\varepsilon\tau_{S/C} = \frac{\sqrt{2}}{2\pi(f_{max} - f_{min})\sqrt{T_{obs} S/N0_{S/C}}}$$

$$\varepsilon\tau_{Q} = \frac{\sqrt{2}}{2\pi(f_{max} - f_{min})\sqrt{T_{obs} S/N0_{QSR}}}$$

ΔDOR future – Related techniques

- Station location
  - ΔDOR could be used to check the position of ESA stations
  - This would be done using for each observation one ESA and one VLBI station which position is already well known
- Phase referencing
  - Phase referencing is a powerful interferometric technique to get absolute differential phase measurements
  - It was used to get a-posteriori results for the descent orbit of Huygens
- Same Beam Interferometry (SBI)
  - SBI is another interferometric technique that makes use of a planetary orbiting S/C to precisely locate another S/C which is in the same antenna beam
  - The technique could be used at Mars, where there are several S/C already orbiting