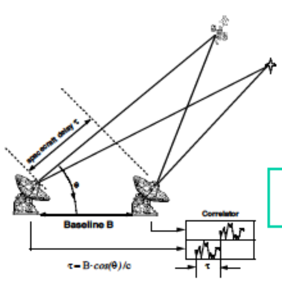
DSN Delta Differential One-way Range

History and Current Operations

26 March 2013

Delta-DOR Engineering
Jet Propulsion Laboratory



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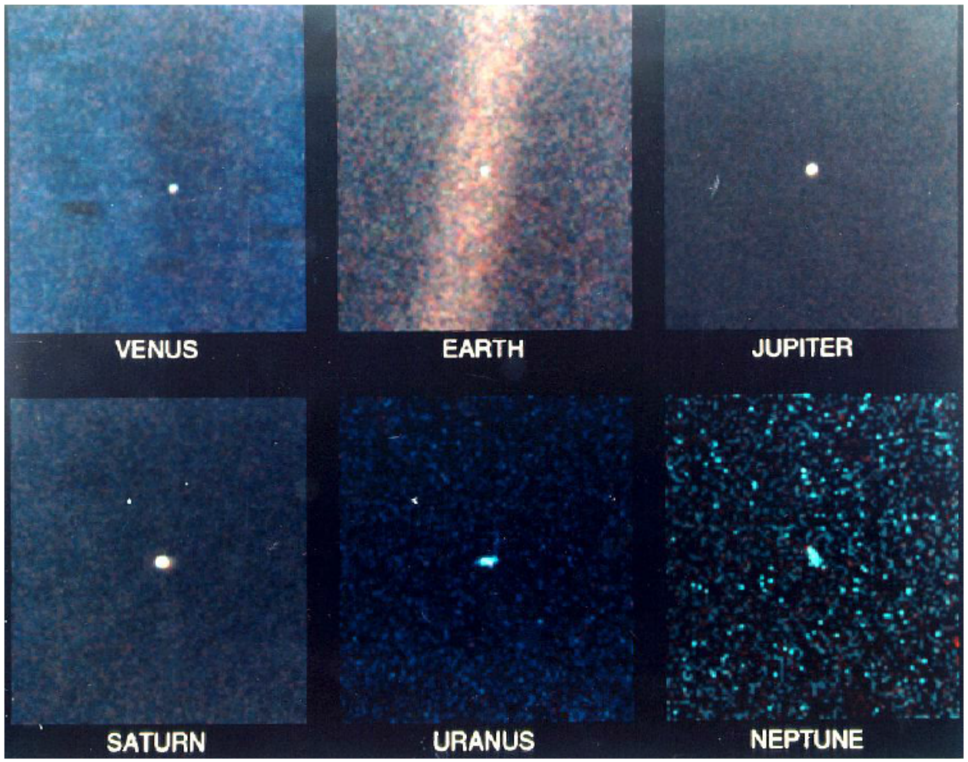
Part I. ΔDOR History

Angle and Distance: What Was Known in 1961 ?



Planetary Images

- Planetary angular coordinates were known fairly well (~1 μrad) from years of optical observations
- The distance scale for the solar system was poorly known – different estimates for the AU differed by 100,000 km
- Original goal for Mariner 2 was to determine AU based on miss distance of Venus flyby

Distance Coordinate Is Improved

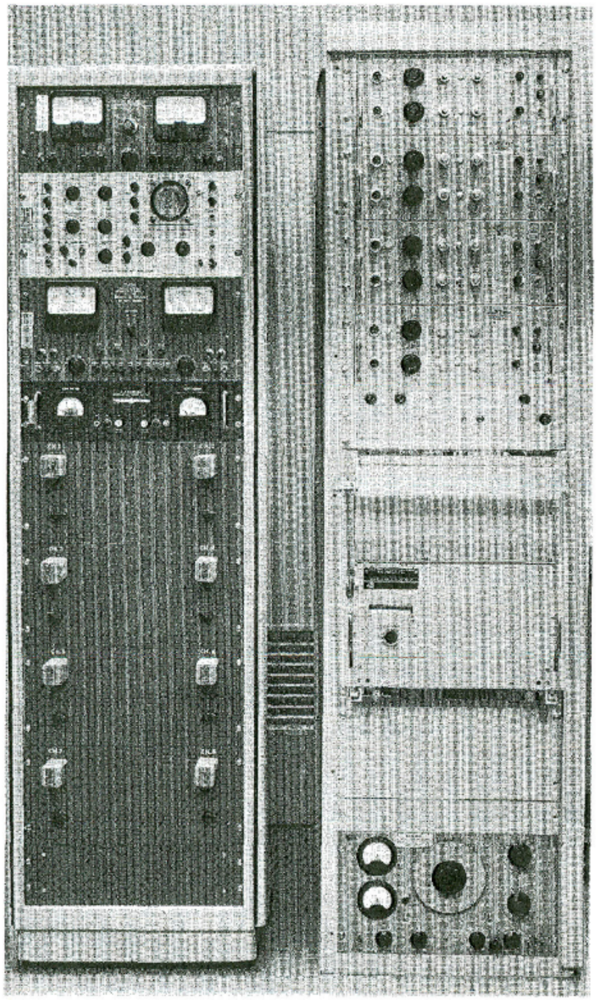


Figure 63. 8-channel receiver and recorder

- Richard Goldstein of JPL made first planetary radar measurements of Venus in March 1961
  - Sensitive open loop receiver and good signal processing algorithm were key
- Within a few months, AU was known to better than 1000 km, an improvement in knowledge of distance by x100
- Mariner 2 trajectory was redesigned and useful scientific data were acquired at Venus flyby in December 1962
- How would angular tracking be improved and how long would it take ?

Navigation and VLBI in the DSN Developed Separately

Navigation Development (1962-1978)

- Doppler Measurement System
- Dynamic and Measurement Models
- Estimation and Filtering
- Higher Radio Frequency
- Range Data Type Introduced
- Media Models

VLBI Development (1971-1978)

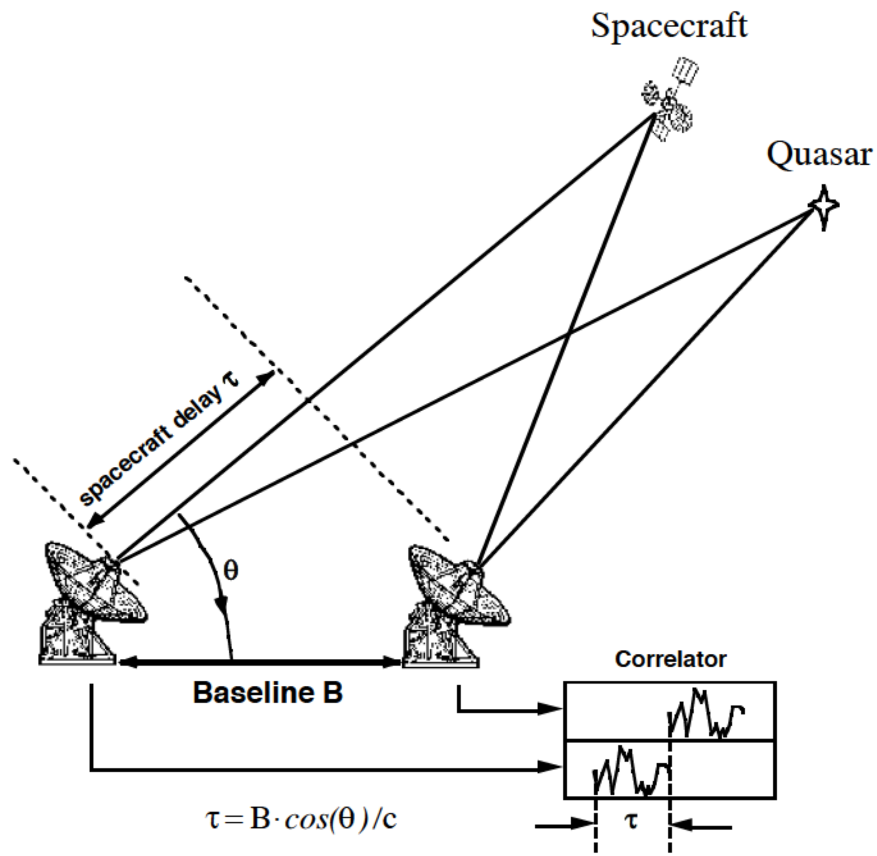
- Celestial Reference Frame
- Precession / Nutation
- UT1 / Polar Motion
- Clock Synchronization
- Station Coordinates
- Media Models

ΔDOR Is Introduced (1979)

- Navigation system had one major deficiency: not sensitive to declination for declinations near zero
  - Voyager Saturn encounters (1980-1981) would be at zero declination
- VLBI tracking of spacecraft was studied to directly measure angles
  - Angular position could be determined more accurately
  - Spacecraft state estimates would be less sensitive to dynamic force mis-modeling
- David Curkendall of JPL realized that a measurement analogous to VLBI could be made using ranging signals
  - Hence the name Delta Differential One-way Range (ΔDOR)
- But various difficulties would slow development

Delta Differential One-way Range

- ΔDOR complements line-of-sight range and Doppler measurements
- ΔDOR uses interferometry to directly measure spacecraft angular position in the radio reference frame
- Development began in the late 1970's
- Accuracy has improved from 150 nrad in 1981 to 2 nrad today
- Many missions have used / will use ΔDOR
- This technique has become more relevant as recent missions have greater navigational challenges
- Observations from 2 baselines are needed to measure both components of angular position



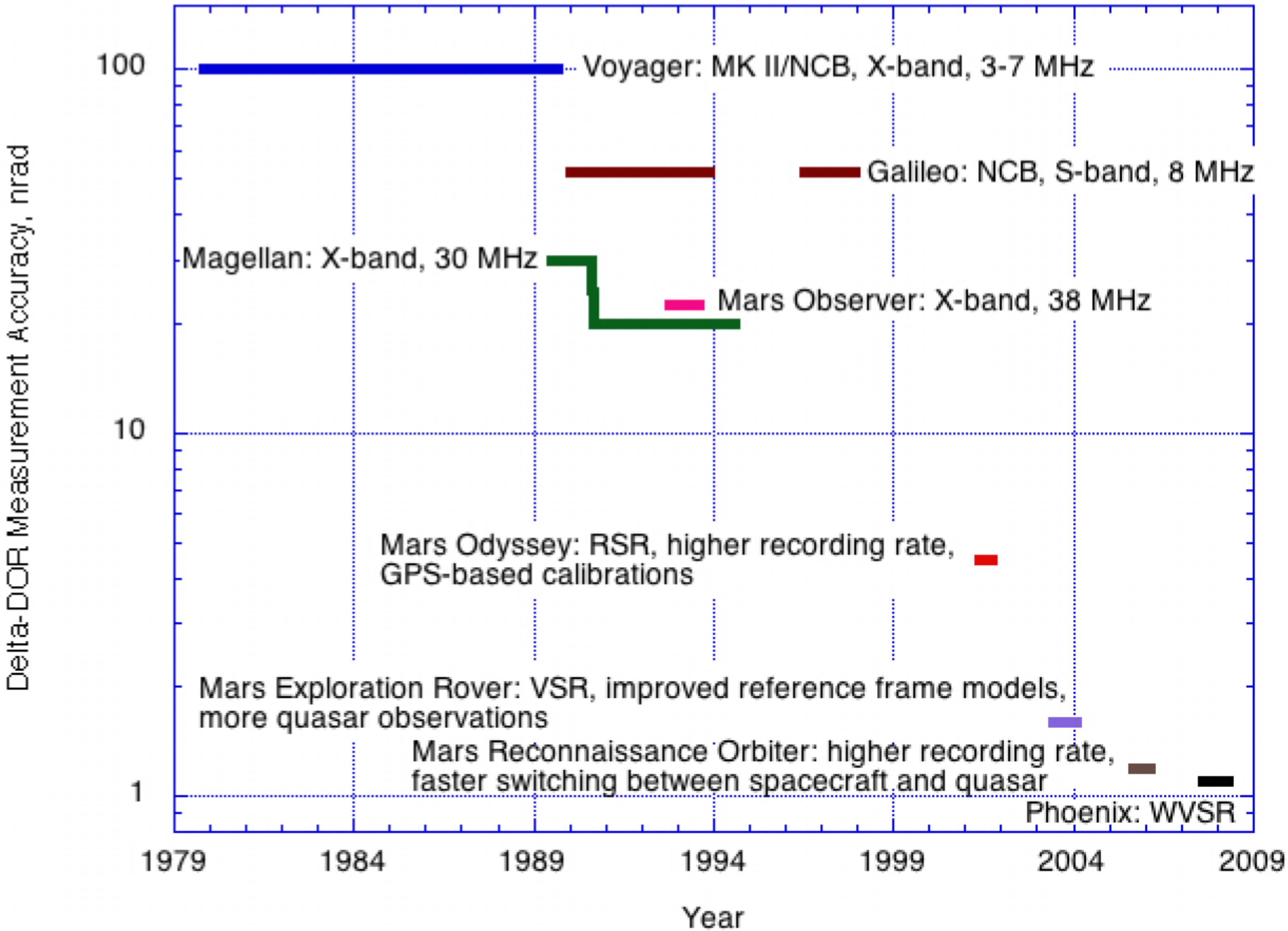
ΔDOR Success Rates over Several Periods

Spacecraft	VLBI System	Period	Number of Scheduled Observations	Success Rate
Voyager	Mk II + ODA	1981 – 1984	144	67%
VEGA	NCB	1985 – 1986	62	97%
Voyager	NCB	1986 – 1987	90	62%
Phobos	NCB	1988	21	81%
Magellan (cruise)	NCB	1989 – 1990	56	86%
Galileo	NCB	1990 – 1992	48	88%
Mars Observer	NCB	1992 – 1993	66	86%
Mars Odyssey	RSR	2001	48	98%
MER1, MER2	VSR	2003 – 2004	131	98%
MRO	VSR	2005 – 2006	65	98%
Phoenix	WVSR	2007 – 2008	105	100%
MSL	WVSR	2011-2012	81	96%

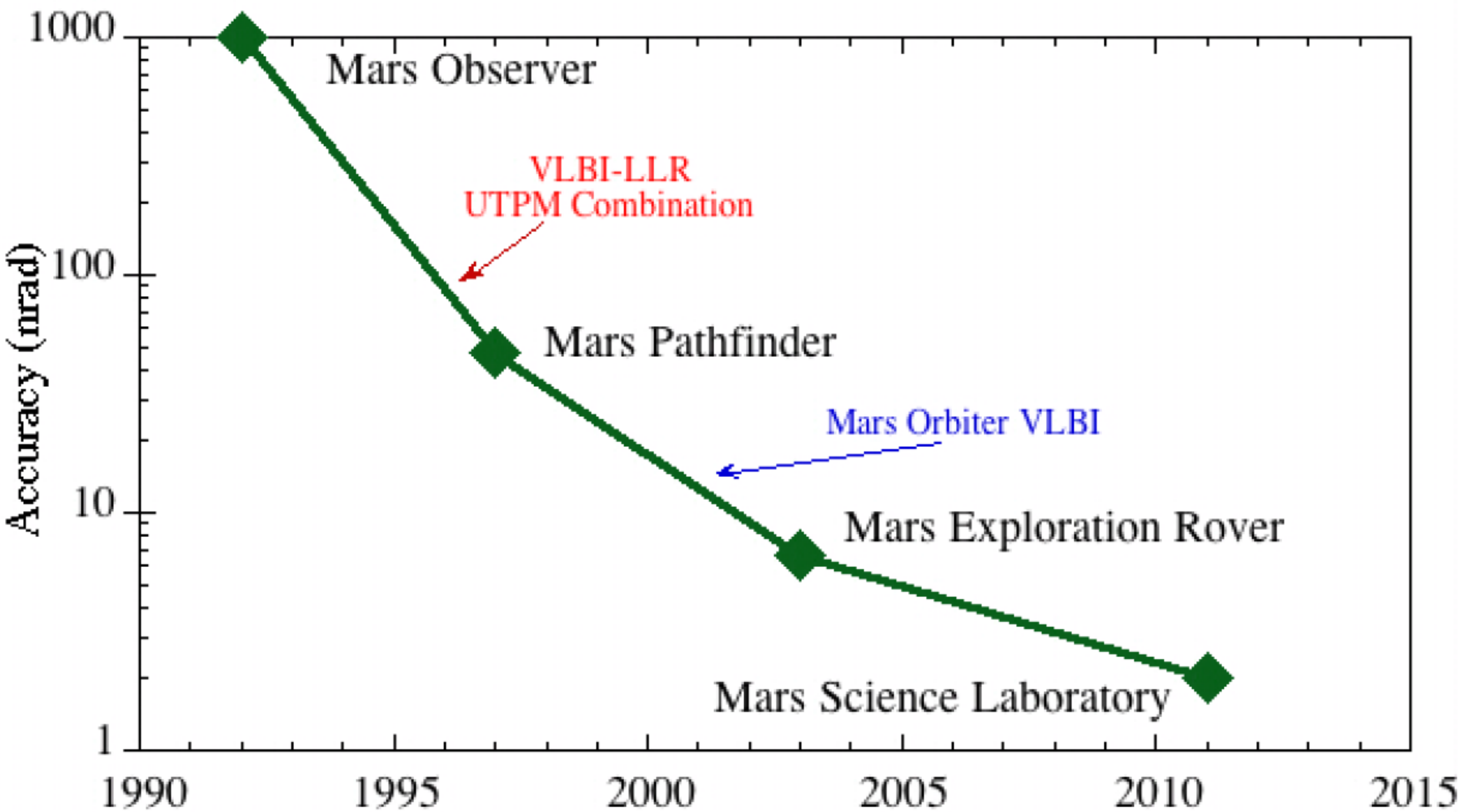
ΔDOR Error Budget Development

- Analyzing factors that contribute to measurement error has been an important aspect of technique
- Accuracy for early measurements was limited by thermal noise and instrumental phase
  - Due to restricted bandwidth of spacecraft signals
- These errors were reduced when 'DOR Tones' were added to spacecraft transponders and recording system was improved
- Focus then shifted to
  - Densify quasar catalog
  - Improve reference frame parameters
  - Improve calibrations for media and earth orientation
  - Improve observational techniques (i.e. fast switching between spacecraft and quasar)

ΔDOR Accuracy Improvements

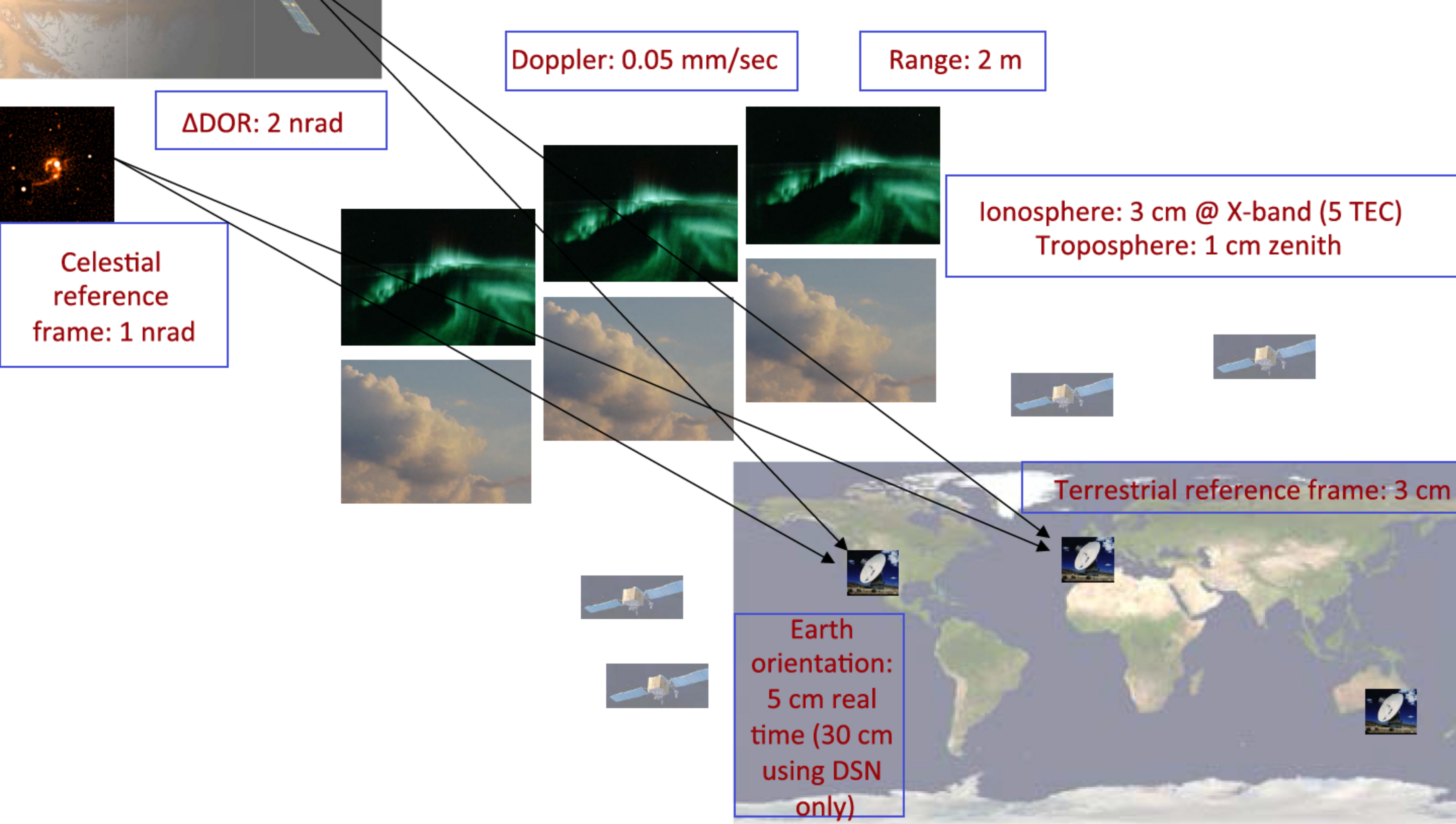


Time History of Project Requirements for Mars Ephemeris Accuracy



Doppler, Range, ΔDOR, VLBI, Earth Orientation, Media Calibrations, Reference Frames

DSN Radiometric Tracking System Performance



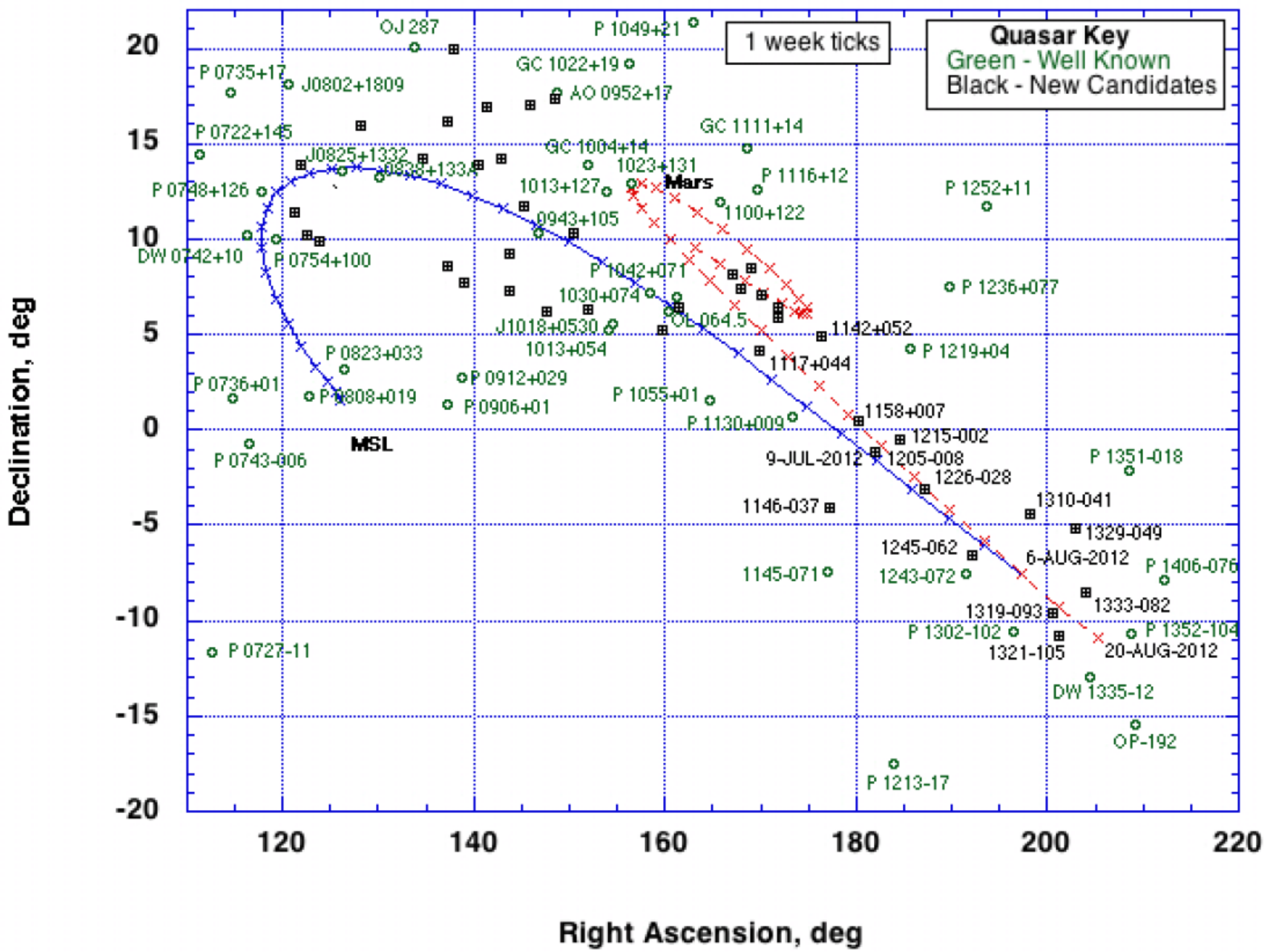
Part II. ΔDOR Current Operations

ΔDOR End-to-End Operations

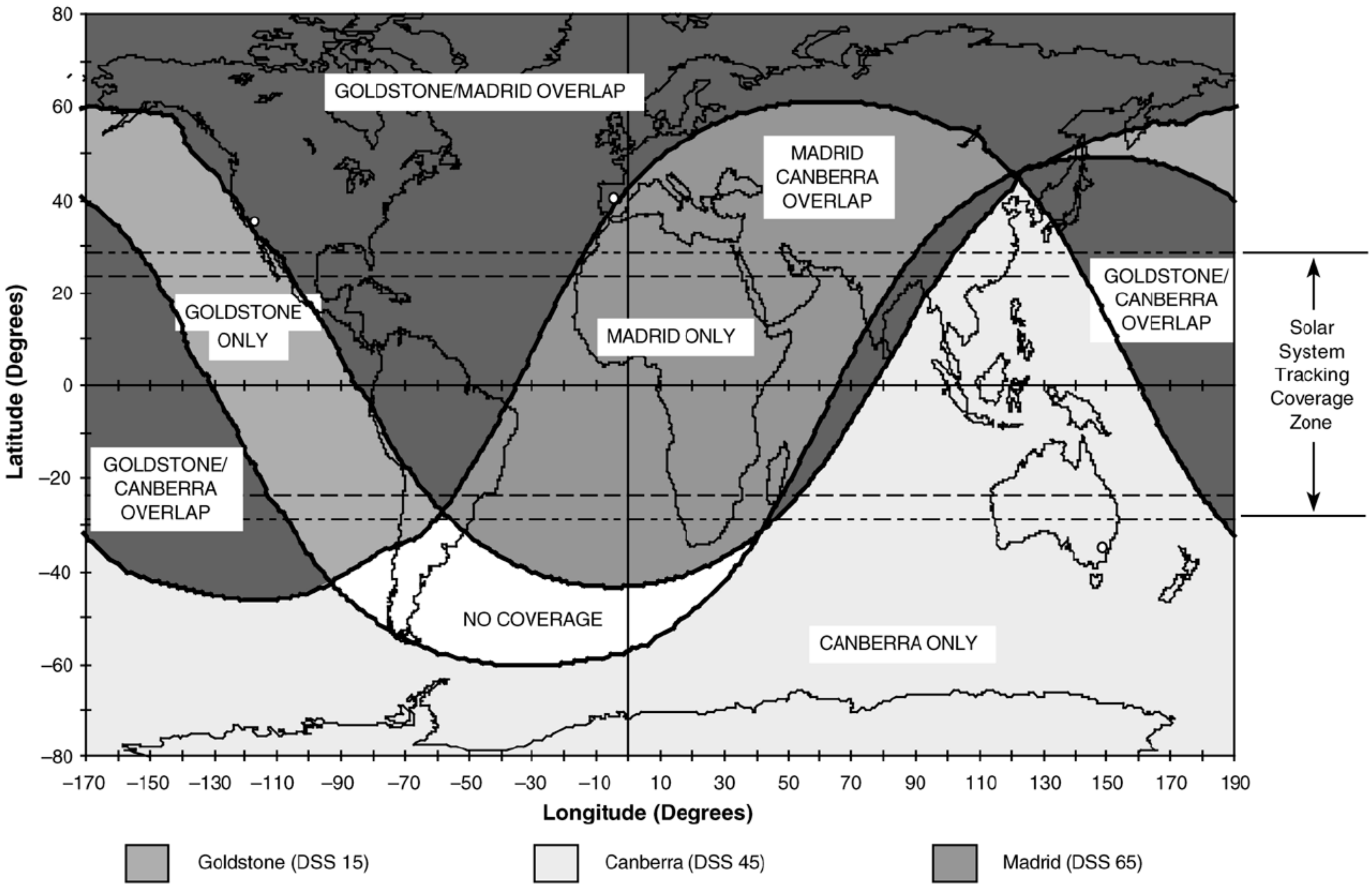
- Mission Planning: A strategy is developed for number of measurements to be requested, to meet navigation requirements
- Scheduling: Two DSN antennas are allocated during view period overlap for each measurement
- Sequencing: A detailed observation sequence is developed for each measurement; spacecraft DOR tones commanded on
- Data Acquisition: Spacecraft and quasar radio signals are recorded open loop using Wideband VLBI Science Receiver
- Correlation Processing: Data are transferred to a common site and correlated to develop time delay observables (typically 48 GBytes reduces to 7 time delay observables)
- Navigation Processing: Measurement models are developed, data are combined, and spacecraft state is estimated

Spacecraft and Quasars in Plane-of-Sky

MSL-2011



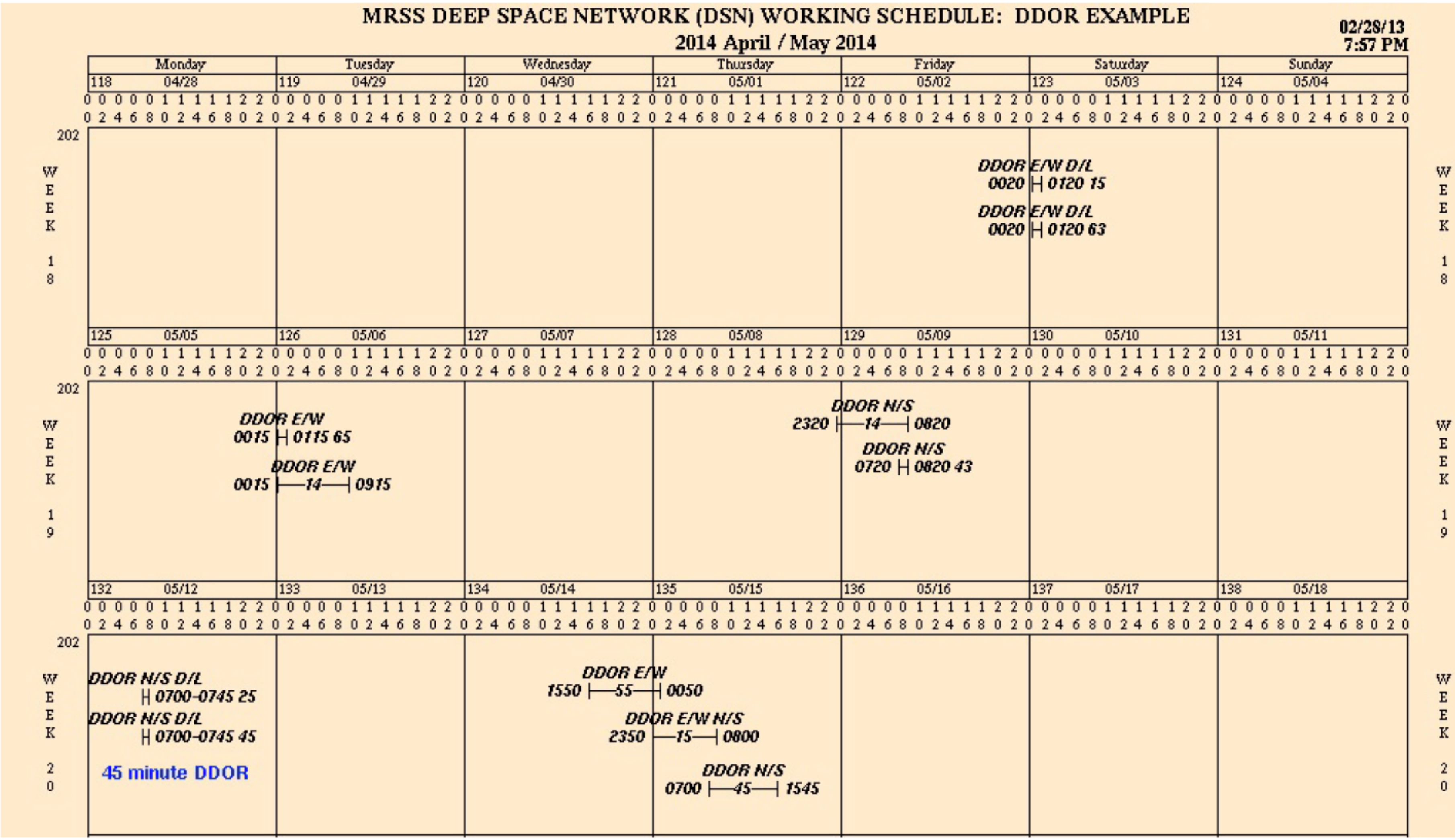
View Period Overlaps



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Description of DSN DDOR Process

- Project scheduler will negotiate tracking passes based on the Requirements

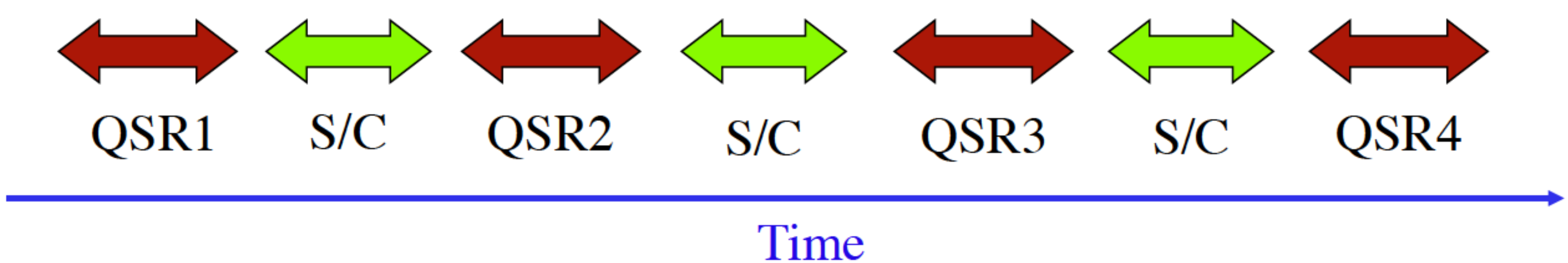


Description of DSN DDOR Process

- A nominal Sequence of Events is developed for all scheduled DDOR tracking passes
- For each scheduled DDOR pass, the DSN will develop a detailed observation sequence, based on spacecraft trajectory, quasar catalog, and stations to be used
- The DSN develops support products to control antenna pointing and frequency channel selection during data acquisition
- Recorded data are transferred to JPL and correlated to generate time delay observables for Navigation

The ΔDOR Measurement

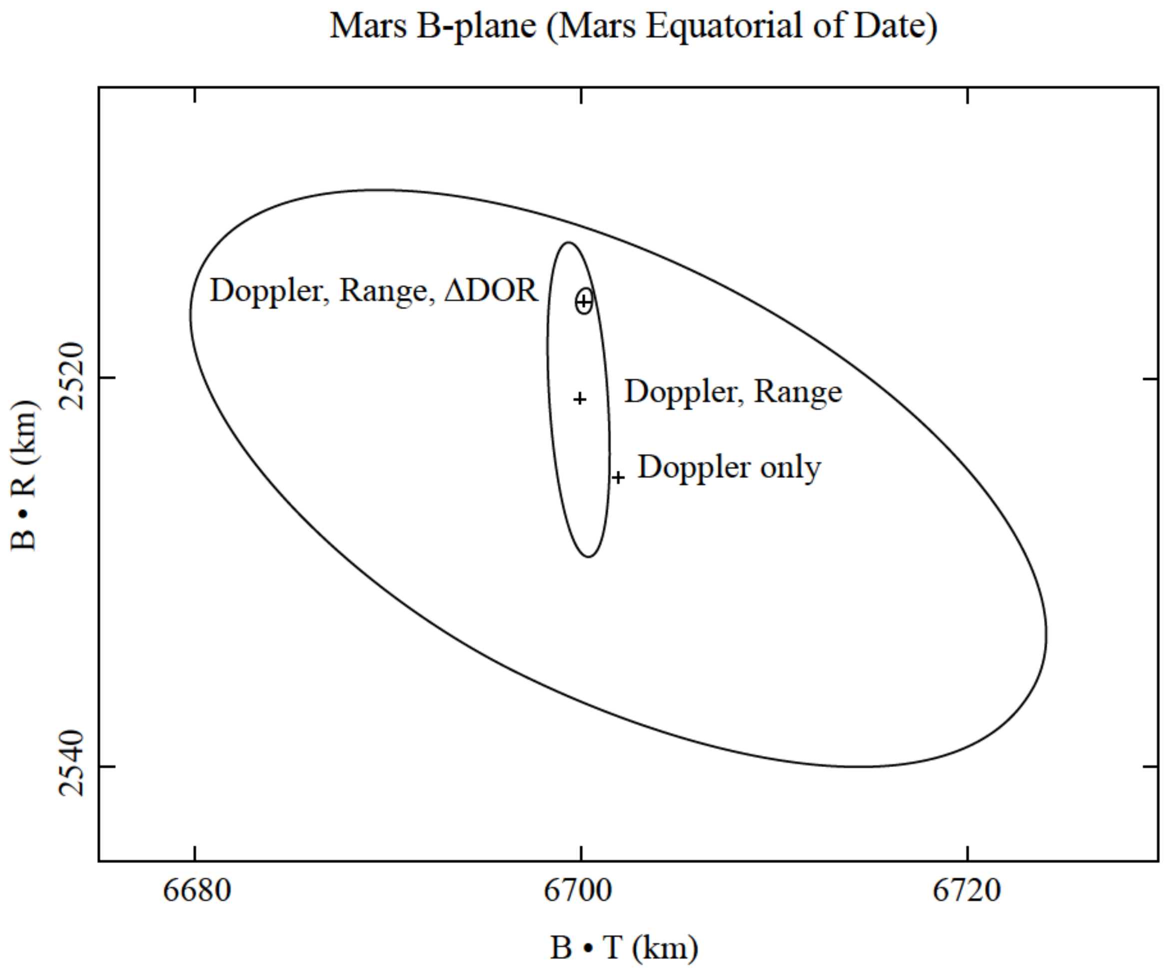
- High rate recordings are made of frequency channels containing spacecraft signals and quasar signals
  - Spacecraft 'DOR Tones' provide wide spanned bandwidth
- Antennas slew from quasar to spacecraft to quasar (QSQ Sequence)
- Several QSQ sequences are recorded in 1 hour
- A time delay observable is provided for each observation of a radio source



ΔDOR Usage for Navigation

- There are two measurement opportunities per day using DSN baselines
  - 2 baselines needed to observe 2 components of angular position
  - Madrid/Goldstone and Goldstone/Canberra baselines are used
- Navigation plans normally call for several measurements on each baseline, for each segment of cruise
  - Additional measurements for maneuvers, flybys, encounters
- Cooperative agreements with other agencies can provide additional baselines and improved geometry for ΔDOR measurements

ΔDOR Benefits: Target Plane Error Ellipses for Several Data Combinations



Orthogonal Baselines from Combined NASA, ESA, JAXA Antennas