Chapter 5
Future Directions in Radiometric Tracking

5.1 Doppler and Range

The precision, versatility, and availability of Doppler measurements have made them the primary tracking data type in the past and will ensure an important future role as well. The advent of X-band uplinks and X-band spacecraft transponders has improved the precision of Doppler observables by a factor of 13 relative to S-band links, due to the reduced effect of charged particles at the higher frequency. If Ka-band radio links are employed, charged-particle effects will decrease, and Doppler measurement precision will improve further. These improvements in accuracy make it possible to better characterize small forces that act on spacecraft, such as those arising from solar pressure, attitude maneuvers, momentum wheel desaturation maneuvers, or gas leaks. However, improvement of dynamic force models in three dimensions may not be possible because of the limited geometry associated with Earth-based Doppler tracking; therefore, improved Doppler data accuracy alone does not guarantee improved radio navigation.

Two-way tracking, where the same ground-based frequency standard is used as the reference for both the uplink signal and for the downlink detector, provides the best Doppler data accuracy today. However, improvements in the stability of flight oscillators may eventually make one-way Doppler tracking competitive with two-way tracking [1]. (This improvement might be achieved through the development of passive linear ion-trap resonators [2] although at the time of publication, flight experiments with these devices are at least 5 years in the future.[1]) One-way tracking simplifies ground-based operations

[1] R. L. Tjoelker, personal communication, Tracking Systems and Applications Section, Jet Propulsion Laboratory, Pasadena, California, May 2000.

and offers a better SNR for the reception of spacecraft telemetry data. The improvement to the telemetry SNR is due to two factors. First, one-way transmissions provide better short-term (< 1 s) stability, resulting in less signal loss in the detection process. This is because the short-term stability of two-way transmissions is degraded by solar plasma scintillations of the uplink signal and, for more distant spacecraft, by thermal noise in the spacecraft receiver. Second, the ground antennas are configured in a listen-only mode for one-way tracking, whereas the more complicated diplexer mode, required for simultaneous uplinking and downlinking, increases the effective system noise temperature of the ground receiver.

One-way tracking has another advantage, with far-reaching consequences. For future missions in which several spacecraft are in orbit about or landed on the same planet, a single deep space antenna can acquire one-way Doppler and telemetry simultaneously from all spacecraft. Multiple uplink signals are not required. Consequently, this configuration results in more efficient use of ground-based resources and enhances orbit solutions and lander position estimates through the use of differential measurements. Simultaneous observations of multiple spacecraft are discussed further in Section 5.4.

Range measurement accuracy is limited today by uncalibrated delays in analog components of spacecraft transponders and ground receivers. Calibration accuracy of the station delay has improved over the last decade, from about 5 m to about 2 m. While precision would appear to be better than 2 m, errors at the 2-m level were still apparent in the mid-to-late 1990s in the Ulysses dual-frequency range data[2] and in Pathfinder X-band data from the Mars surface [3]. Further reduction of this systematic error component may remain a challenge due to the narrow bandwidth of deep space ranging codes. At the same time, an improvement in link margin and a reduction in the random measurement error are expected as future transponders provide a regenerative ranging capability [4]. Nonetheless, systematic errors at the meter level, due primarily to uncalibrated instrumental effects, are likely to remain.

Combining range and interferometric observables is an alternative to using long, continuous Doppler arcs for cruise navigation. In this method, the three components of spacecraft position are directly measured in just a few minutes, using range and interferometry. Doppler data may then be applied to infer better force models, without the fear of aliasing model parameters into weakly observed spacecraft state components. In addition, simultaneously fitting all data types leads to improved navigation reliability and robustness. Furthermore, if they were available, range measurements with submeter accuracy would have application to the relative tracking of planetary orbiters, rovers and landers [5].

[2] W. M. Folkner, personal communication, Tracking Systems and Applications Section, Jet Propulsion Laboratory, Pasadena, California, April 2000.

5.2 Very Long Baseline Interferometry

The first-generation operational DSN VLBI system has provided angular spacecraft measurements with an accuracy of better than 50 nrad. The next-generation system implementation incorporates numerous design improvements to increase the operability, reliability, and accuracy of VLBI measurements. Utilizing spacecraft DOR tones with a spanned bandwidth of 38 MHz, VLBI observable precision and instrumental calibration will be at the 5 nrad level or better. Measurements of ΔDOR at this accuracy level are expected to contribute to the approach navigation for orbiters and landers being delivered to Mars and elsewhere.

The VSR (the next-generation VLBI system) is based on the Full Spectrum Recorder. The FSR is an open-loop receiver that can downconvert and record selected portions of the RF spectrum. The FSR has been used in the DSN for Galileo telemetry arraying since 1996 [6,7] and has an outstanding record in terms of reliability and operability. Real-time spectrum displays are used to verify signal acquisition. In addition, internal timing and precision are designed to allow combining of signals from multiple antennas spanning intercontinental distances. The algorithms used in arraying to align the signals prior to combining are closely related to those used for VLBI signal processing; therefore it is a small conceptual step to evolve the FSR into a VLBI system.

The FSR has open-loop multiple-channel recording capability. The input is a broadband intermediate-frequency signal that has been downconverted from radio frequency. This input is digitally sampled at 256 Msamples/s. All subsequent downconversion and filtering steps are digital. This preserves the phase relationship between components of the signal being measured (for example, DOR tones) and eliminates the introduction of instrumental errors during baseband downconversion and filtering. Up to four independent channels of bandwidth, 16 MHz each, may be placed anywhere within the 128-MHz input. Selected portions of the baseband channels may be recorded in bandwidths ranging from 1 kHz up to 16 MHz. From 1 to 16 bits/sample may be selected. Typical operation is expected to record four channels of spacecraft data, centered on the carrier and DOR tones, at 8 bits/sample and 2 Ksamples/s. Quasar data would be recorded in four channels centered at the same frequencies, using 2 bits/sample and 2 Msamples/s. This recording strategy is chosen to balance errors caused by dispersive instrumental effects against errors caused by SNR.

The higher channel sampling rate, multibit samples, and the use of parallel rather than time-multiplexed channels are the keys to improved measurement precision. In the example cited in Fig. 4-2, the error due to quasar SNR was 9 nrad, using the NCB VLBI system and assuming a source strength of 0.4 Jy, a 70-m and 34-m DSN antenna pair, and 10-min integration time. With the VSR, that error drops to 3 nrad, still assuming a source strength of 0.4 Jy, but now using a 34-m and 34-m DSN antenna pair and 20-min integration time.

Recorded data are transmitted through the Ground Communication Facility to the Network Operations Control Center at JPL, where data from two stations are combined to form interferometric measurements. At data transmission rates readily achieved today, future observables could be delivered to navigation teams within an hour of data acquisition.

Angular measurements accurate to better than 50 nrad will continue to require quasar observations. Even though interstation clock synchronization approaches the nanosecond level today using GPS, path delays through the specific instrumentation used to record spacecraft tracking data cannot be known a priori to this level. A real-time calibration is required. For intercontinental VLBI measurements, quasar signals are the reliable and available source for instrumental calibration.

The VLBI system upgrade, scheduled for 2001, and the calibration system improvements discussed in Section 3.4 both contribute to improved ΔDOR accuracy. Figure 4-2 contrasts the performance of the previous VLBI system, using calibrations available in 1992, and the next VLBI system, labeled 2001, using calibrations available today. The figure shows an example of performance corresponding to the assumptions given in Tables 3-3 and 4-1. Actual performance, however, may vary by a factor of two or more, depending on specific geometry and spacecraft hardware.

5.3 Connected-Element Interferometry

Interferometry using antennas separated by tens to hundreds of kilometers has the potential to determine spacecraft angular position at the 50-nrad level [8]. When all system elements are connected via high-speed data lines to a local real-time correlator, the technique is known as connected-element interferometry (CEI). When CEI is used, it is possible to obtain observables in real time at the tracking site. Moreover, on-site processing allows real-time validation of successful data acquisition, a feature highly desired by DSN operations personnel and the flight projects.

CEI performance depends heavily upon the separation of the receiving antennas. At present, separations between operational stations within any of the three DSN complexes are less than 10 km; hence, the DSN is currently unable to support this type of measurement. There is, however, at the Goldstone complex, a telecommunications research and development station that is 21 km from the other antennas. Tests conducted at Goldstone demonstrate the utility of CEI for navigation [9]. An array of antennas spread out over a suitable distance could provide this capability.

5.4 Same-Beam Interferometry

When two spacecraft are so close in an angular sense that they may be observed in the same beamwidth of an Earth-based radio antenna, differential interferometric observables may be generated using simultaneous observations of the two spacecraft from two deep space antennas. This technique, illustrated in Fig. 5-1 and known as same-beam interferometry (SBI), provides extremely accurate relative position measurements in the plane-of-the-sky, complementing the line-of-sight information from Earth-based Doppler and range measurements. System errors that scale with angular and temporal separations are greatly reduced, allowing nearly the full precision of carrier-phase measurements to be utilized. The concept of differential tracking for angularly close sources is well established and has been applied to numerous astronomical problems [10–13]. Furthermore, improved orbit determination using this technique was demonstrated with the Pioneer Venus and Magellan orbiters at Venus [14,15]. The next-generation VLBI system implementation, described in Section 5.2, could provide the means for operational use of this technique.

As more spacecraft begin operating at Mars, SBI could be used to improve orbit determination while requiring fewer Earth-based tracking resources. All spacecraft within Mars stationary orbit would be visible within the 1-mrad beamwidth of a 34-m antenna at X-band. All signals would be acquired simultaneously. SBI data acquired during ground-station overlaps could provide enough geometric data strength to offset the loss of long arcs of ground-based two-way Doppler measurements. One-way Doppler combined with SBI may meet navigation requirements, eliminating the need for multiple uplinks.

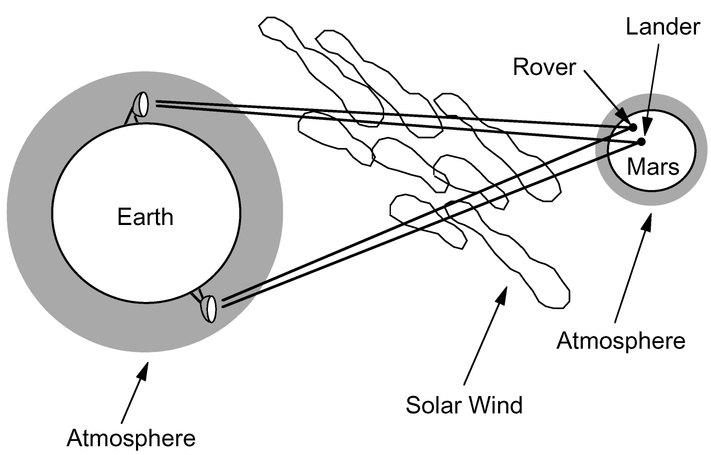

Fig. 5-1. Same-beam interferometry measurement geometry.

SBI offers a significant performance advantage over conventional spacecraft-to-quasar ΔDOR. Figure 5-2 shows an error budget for SBI measurements of two Mars orbiters. Some appreciation of the accuracy improvements afforded by this technique can be gained by contrasting Figs. 4-2 and 5-2. In Fig. 5-2, the dominant SBI error is due to solar plasma; this error does not cancel as completely as other media errors, since the four SBI ray paths are at a maximal spatial separation in the interplanetary space between Earth and Mars. A 20-deg Sun-Earth-probe angle and 5-min data averaging were assumed for this calculation. For an Earth-Mars distance of 1.5 astronomical units (AUs), the root-sum-square (rss) error of 36 prad corresponds to an 8-m error in the determination of one component of the relative position of the two spacecraft.

Also shown in Fig. 5-2 is an error budget for two vehicles on the surface of Mars. The SBI measurement accuracy for a rover and lander is a factor of three better than that for two orbiters. The difference is due to the much smaller angular separation between the rover and the lander. Differential data from a landed spacecraft and from an orbiter help to determine the absolute position of a spacecraft on the surface of Mars, especially the distance from the equatorial

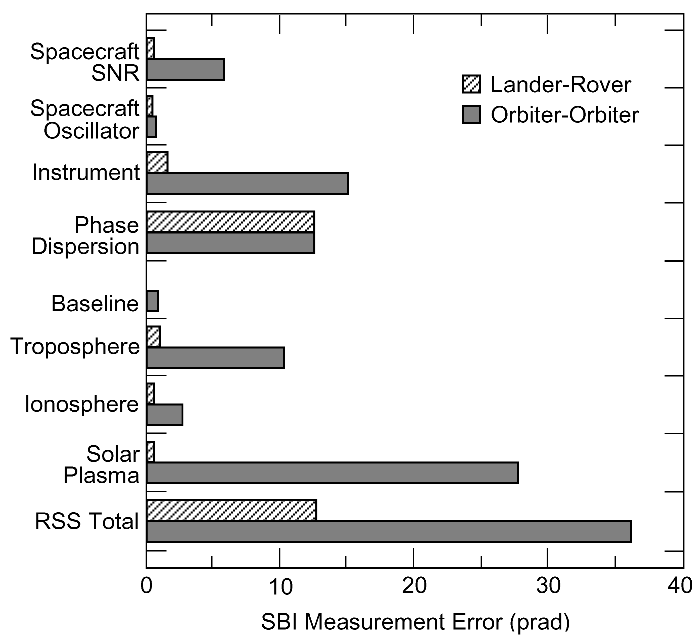

Fig. 5-2. Error budget for same-beam interferometry measurements for a lander and rover on the surface of Mars and for two spacecraft in orbit about Mars. X-band radio links and a Sun-Earth-probe angle of 20 deg are assumed.

plane. Using SBI, the position of the landed spacecraft is established with respect to the center of mass of Mars because differential data tie it to the orbiter, which is itself tied to the Mars center of mass through dynamics.

Although in situ measurements may become the primary technique for precise positioning of vehicles on the surface, SBI could be useful as part of a global navigation strategy or as a backup capability.

5.5 Spacecraft-to-Spacecraft Tracking

Historically, interspacecraft metric tracking has seen only limited use in the planetary exploration program. However, the recent emergence of mission concepts involving constellations of spacecraft flying in precise formation (such as the planned interferometry missions of the NASA Origins Program) and the expected need for highly accurate close proximity and/or in situ tracking in Earth orbit, at Mars, and elsewhere, have prompted the design of new flight instruments for interspacecraft microwave tracking and communications. Receivers and transceivers for the most demanding microwave tracking applications will benefit from two decades of GPS precise tracking technologies.

Beginning in the early 1980s, JPL developed the Rogue family of GPS ground receivers. These receivers were initially built to provide ionospheric calibrations at the DSN tracking complexes. The Rogue design also met the needs of the geodetic community for precise measurement of crustal motion and precise positioning of low Earth orbiters. Ground-breaking performance was achieved through the use of new digital technology that allowed simultaneous, dual-frequency tracking of both carrier phase and pseudorange from as many as eight GPS satellites. The receivers used P-code when it was available, but could switch to codeless operation when the military turned on anti-spoofing [16].

The TurboRogue family of receivers was an extension of the Rogue design; it was developed primarily by the NASA Solid Earth and Natural Hazards Program. These receivers incorporated emerging compact, low-power, digital technology to substantially reduce receiver size, weight, and power [17]. These characteristics enabled portable operations and access to remote areas. Performance enhancements also made the TurboRogue attractive for fixed ground network operations, and many have been installed in the IGS global network [18]. Modified versions of the TurboRogue were flown on several satellites, beginning with the GPS Meteorology Experiment, known as GPSMET [19].

More recently, a family of flight receivers has been developed at JPL as an extension of the TurboRogue family of GPS ground and flight receivers [20]. The new receivers, generically referred to as the Blackjack family, are designed to support precision orbit determination for altimetric, radar, and other remote-sensing missions, and to also provide valuable measurements of Earth's atmosphere and ionosphere [21–23]. Using as many as 16 parallel channels, they simultaneously acquire dual-frequency GPS carrier-phase and pseudorange measurements. These measurements have improved precision relative to the TurboRogue measurements, due to the addition of a patented, enhanced-codeless tracking technique [24].

For NASA's 2001 Gravity Recovery and Climate Experiment (GRACE) mission, the receive-only GPS instrument design described above has been altered to include satellite cross-link ranging capability and star tracker processing [25]. GRACE will place two satellites separated by about 220 km in coplanar, near-polar orbits, at an altitude of 300 to 500 km. Precise measurements of the differential gravitational effects on the spacecraft, detected through variations in their separation, will enable determination of the Earth's gravity field to unsurpassed accuracy and resolution [26]. The GPS tracking data acquired on each satellite will enable precise orbit determination, while the intersatellite ranging and two accelerometers (one on each spacecraft) will provide the required gravity field information. GRACE mission requirements mandate that spacecraft separation need only be controlled to $\pm$ 50 km, but variations in separation must be measured to a precision of a few microns [26]. The cross-link radio design provides transmit and receive capability at 24.5 GHz and 32.7 GHz, enabling biased range measurements with approximately one-micron precision [27].

The interspacecraft tracking concept is central to the design of a related instrument, referred to as the Autonomous Formation Flyer (AFF). The first AFF, termed the Constellation Communications and Navigation Transceiver (CCNT), will fly on Space Technology 5 (ST-5), a NASA 2003 mission to demonstrate nanosatellite constellation technologies. This mission will fly three satellites in highly elliptical Earth orbits having 200-km perigee and ~40,000-km apogee, with the objective of measuring the effects of the Sun on Earth's magnetic field. The CCNT will provide communication as well as cross-link ranging.

Another version of the AFF will fly on ST-3, to be launched in 2005. This mission will place two spacecraft in formation at the libration point, L1, of the Sun-Earth system. The primary objective of the mission is to validate technologies leading to a future deep space constellation in tight formation, called Terrestrial Planet Finder [28]. The AFF, with a Ka-band cross-link and three antennas on each spacecraft, will provide coarse relative positioning of the two spacecraft to an accuracy of 1 cm and bearing information to an accuracy of 1 arcmin. A separate optical metrology unit with a precision of 1 nm will then enable spacecraft control to 5 cm [29].

A transceiver derived from the AFF and designed for cross-link communication and precise range and range rate capability has been under study for a future communications and tracking network at Mars. The envisioned "Marsnet" would feature as many as six satellites in low orbit (~800 km) and possibly another in areostationary orbit. This network could communicate with science orbiters, incoming spacecraft, or landers and rovers on the surface of Mars that carry compatible radio systems [30]. While the network transceivers could be capable of autonomous, onboard orbit determination and operation, initial satellite operations would most likely be supported autonomously on Earth. Marsnet users, equipped with compatible radios, could receive range and range rate data, as well as satellite ephemeris information, from all orbiters in view.

From a navigation perspective, the potential benefits of such a constellation are impressive. Spacecraft approaching Mars could use onboard ranging to one or more orbiters for real-time determination of position prior to aerocapture or entry-descent-landing exercises. Early study results indicate that the use of one-way Doppler data from a single Mars orbiter could enable radio-only position determination one day prior to encounter to 200–300 m,[3] which is an improvement of nearly an order of magnitude, relative to Earth-based tracking strategies. These results assume that both spacecraft carry an ultrastable state-of-the-art oscillator. Entry-descent-landing capability using the Marsnet would depend upon constellation design, particularly the number of satellites in common view of the user. For example, with continuous tracking from three properly spaced Marsnet orbiters at 800 km, a descending spacecraft equipped with a network transceiver and an inertial measurement unit (IMU) could determine its position in near-real time (1-min latency) to 50 cm or better.[4] With only two-satellite coverage, this accuracy degrades to the meter level. Likewise, elements on the surface with three or more Marsnet satellites in view, could determine their positions in near-real time to a few decimeters.[5]

The transceiver concept envisioned for the Marsnet has broad implications for future space missions. First, integrated tracking and communications functionality will ensure the concept's multimission utility while conserving spacecraft power and mass. Second, high-precision radiometric tracking capability, including range, range rate, and direction-finding measurements, will be attractive for complex navigation applications involving multiple spacecraft. Third, the architecture inherited from the GPS Blackjack receiver is highly adaptable and configurable. This flexibility can be attributed to its software-intensive modular design, which enables additional capabilities to be readily incorporated, even during flight. For a relatively long-lifetime instrument, the ability to upgrade in flight can be quite valuable. Moreover, the ease with which new

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[3] T. A. Ely, personal communication, Navigation and Flight Mechanics Section, Jet Propulsion Laboratory, Pasadena, California, July 2000.

[4] Y. E. Bar-Sever, personal communication, Tracking Systems and Applications Section, Jet Propulsion Laboratory, Pasadena, California, July 2000.

[5] Ibid.

requirements can be added to the existing architecture will translate into cost savings for future missions. As an example, the upcoming Laser Interferometer Space Antenna (LISA) mission (scheduled to launch in 2009) [31] will require metrology precision to the level of picometers and control to the level of nanometers. To accomplish this, the transceiver can be adapted to utilize an optical ranging system together with the existing baseband processor.

In summary, future deep space missions are expected to place new requirements on flight communications and navigation systems. The highly precise formation control of space interferometers as well as stringent navigation requirements at Mars and other target bodies will continue to drive the development of more capable flight transceivers. Consequently, spacecraft-to-spacecraft tracking and communications technologies are likely to receive unprecedented emphasis during the first decade of the 21st century.

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