The Role of Clocks in Operating Deep Space Missions*

S. W. Asmar and E. R. Kursinski
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

Abstract

Operation of deep space missions requires stable frequency references and clocks to perform several mission critical functions. These references are used in generating the telecommunication links to maintain communications between earth and spacecraft, in generating accurate doppler, range and VLBI observables for determining the spacecraft's time varying position, and to generate on-board timing information for clocking out timed commands and time tagging instrument data. In addition, science applications exist particularly those utilizing radio instrumentation which can require additional functions and levels of performance. The design necessary to support these functions affects both the spacecraft and the ground tracking stations. This paper provides a brief description of these functions and some of the key requirements needed to support them.

I. Introduction

The operation of deep space missions require the utilization of stable clocks and frequency references to perform several mission-critical functions both on-board the spacecraft as well as at the ground tracking stations. The telecommunications link needed to maintain communications between earth and the spacecraft is derived from these oscillators. They play a role in the following functions: on-board timing, telemetry, navigation, and science. Though there is potentially substantial overlap, these functions are typically supported by distinctly different clocks on-board the spacecraft. The design necessary to support these functions affects the ground tracking stations as well. Navigation data observables as well as certain radio science experiments require ground-based hydrogen maser clocks to provide superior stability (in terms of Allan deviation at longer integration times) over crystal oscillators.

II. On-Board Timing

As part of the spacecraft's command and data handling subsystem, the on-board clock has the function of generating timing information for clocking-out stored commands and time tagging payload data. The on-board timing clock provides timing signals needed to time tag events observed

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by the different spacecraft engineering subsystems and science instrument payload. The time-tagged data is either transmitted to earth in real-time or recorded on data storage units for telemetry transmission during some period following the flyby.

Typically based on redundant crystal oscillators operating at or near 5 MHz, the data handling clock is stable to 5×10^{-9} over any one minute. The oscillator signal is divided into clock frequencies ranging from 0.25 Hz to 640 kHz which are then distributed to engineering and scientific subsystem users. The clock provides a time code that is inserted in the data packets. The time code may contain 40 bits divided into a coarse and fine time segments and is transmitted once every second. The coarse time code, 32 bits, is a straight, continuous binary count of seconds with the LSB being 1 second. Its period is 2^{32} seconds, or 136 years. The fine time code, 8 bits, is a straight count of binary fractional subseconds with the LSB being 1/256 seconds.

Execution of complicated sets of stored commands is required to successfully operate a complicated planetary mission particularly in the outer solar system. As Voyager 2 approached Neptune, the time delay from command transmission to reception at the earth of the spacecraft command confirmation was more than eight hours. The magnitude of this delay was comparable to the entire close-up flyby period making autonomous spacecraft operation an absolute necessity. In general for planetary missions, the spacecraft must act as a robot executing a precisely timed series of preprogrammed command sequences by relying on an on-board clock to determine proper execution time. These commands are carefully designed on earth, up-linked and stored on-board the spacecraft as much as a year prior to the flyby (subsequent modifications are up-linked as necessary). During a close flyby, the required accuracy of command execution timing can be a fraction of a second. To achieve this precision during the long Voyager mission the clock was seldom corrected; instead, the clock drift was continually monitored during the months prior to each flyby, the offset estimated and the execution times of command sequences then shifted to compensate for the anticipated clock error.

The tightest requirements on execution time accuracy occur when the spacecraft flies very close to an object of interest causing the geometry to change very rapidly. In the case of the Voyager Neptune flyby, the tightest requirement was driven by the "limb-tracking" maneuver executed during the radio occultation observations of the planet's atmosphere. This maneuver is executed while the spacecraft flies behind Neptune as viewed from the earth. It maintains the spacecraft orientation such that the three meter telecommunications antenna is pointed at the location in the planet's atmosphere where the image of the earth appears in order that the spacecraft's signal can be received on earth throughout the occultation period. The narrowness of the spacecraft antenna beam and the rapidly changing geometry required an execution accuracy of approximately one second. The combination of the clock drift and navigation uncertainties required this command sequence to be updated about one week prior to the encounter.

III. Telemetry

In deep space communications, the design chosen to get science and engineering data from the spacecraft to the earth phase modulates the data onto a video frequency subcarrier which is modulated onto a microwave carrier signal [1]. This requires three oscillators: one to generate the carrier signal, one to drive the subcarrier signal, and the data rate clock. These oscillators are separate and independent of one another to avoid coherent spurious signals which can severely degrade the accuracy of the data recovered in the demodulation process. The oscillator from which the carrier signal is derived is a crystal oscillator either free running or voltage controlled to maintain phase-lock with the up-link signal from earth. The free running type is either an auxiliary oscillator, provided as part of the spacecraft's standard transponder, or an "ultra-stable" oscillator (USO), which is available on certain deep space missions as instrumentation for radio science experiments and will be discussed further under the role of clocks in science. Free running oscillators are used when communication is in the "one-way" doppler mode where no uplink from the ground is either necessary or available. The voltage controlled oscillator (VCO) is used when the spacecraft is in two or three-way mode of communication with ground stations and the uplink signal is used as the phase reference for the downlink carrier signal. The one-way mode is simpler and more robust whereas the VCO mode is typically used when range and doppler navigation data is also required.

The second clock which drives the subcarrier is a free running crystal oscillator in the telemetry modulation unit. The third clock, the data rate clock is a crystal oscillator residing in the command and data handling subsystem discussed in the previous section.

From a telemetry standpoint, the primary requirement is that these oscillators be phase coherent over the time scales important to phase modulation and demodulation. This is required in order that the phase modulation be readily detected in the presence of the natural variability of the reference signal phase. Deep space data rates generally range from a few bits per second to hundreds of kilobits per second implying time scales ranging from microseconds up to a second. This type of requirement leads to frequency stability requirements on the order of 10^{-11} at 1 second for the carrier signal oscillator. In practice, the auxiliary oscillator, the telemetry modulation unit clock and the command and data handling clock are all of comparable stability.

IV. Navigation

Oscillators and clocks are used in navigation to generate accurate doppler, range, and very long baseline interferometry (VLBI) observables for determining the spacecraft's position as a function of time. Deep space missions are generally navigated via radio tracking where signals are typically referenced to ground-based clocks such as hydrogen masers in two or three-way coherent doppler modes. Optical navigation is used on some missions when the spacecraft is sufficiently close to an object that pictures are useful indetermining its position relative to the object.

There are three categories of radio navigation data types: range, range rate (doppler) and VLBI. Range and range rate are measurements of path length and change in path length along the line of sight between the earth and spacecraft. By observing the change in the path length as the earth rotates one can also determine the spacecraft angular position in the plane of the sky [2]. VLBI directly measures the spacecraft angular position and its rate of change. The range and VLBI type measurements are orthogonal and therefore complementary in determining spacecraft position.

Following the discussion of [2], a range observable is a measure of round trip light time (RTLT) as recorded by the station clock

$$r_k = ST(t_k) - ST(t_k - RTLT) \tag{1}$$

where $ST(t_k)$ is the time as kept by the station clock at true time t_k. A doppler measurement d_k is defined in terms of differenced range by:

$$d_k = \frac{r_{k-1} - r_k}{T_c} \tag{2}$$

where $T_c = t_{k+1} - t_k$ is the doppler count time.

It is clear from these simple expressions that two of the relevant time scales are the signal integration time (on the order of seconds to minutes) and the RTLT (minutes to hours). The duration of the station's tracking pass (≈12 hours) is also important particularly for determining the angular position. With the present performance of hydrogen masers used in the DSN, the clock is generally not the limiting error source in two and three way doppler or range measurements. A more detailed description of the error budget in the navigation observables is given in **[2]**.

One-way doppler measurements are seldom used at present because of the instability of spacecraft oscillators. However, as spacecraft oscillators continue to improve one-way doppler may be used more frequently. One obvious scenario is the case where a number of spacecraft are in orbit around a planet or residing on its surface. It would be desirable to have a navigation system which did not require separate stable uplink signals to each vehicle. If sufficiently stable oscillators could be placed on each vehicle, then all navigation could be done utilizing one-way links with a single ground tracking antenna dramatically reducing the complexity of the ground equipment requirements and operation.

In VLBI, the relative delay between the arrival of a signal received at a small set of widely spaced sites is measured. This delay is a function of the angular position of the spacecraft. Because the receive sites are so widely separated, independent clocks must be used at each site. Any clock errors cause an error in the measured delay creating an error in the inferred angular position. This would cause clocks to be a major error source in VLBI measurements except that a differential observational technique is used to remove many of the instrumental effects including that of the clocks. The technique is simply to sequentially observe the spacecraft and a natural radio source whose angular position is well established. In this way the spacecraft's angular position is measured relative to the radio source and many of the common mode error sources such as clocks simply cancel.

V. Science

Scientific experiments utilizing radio instrumentation have evolved largely out of the navigation capability and can require additional clock functions and levels of performance. These experiments can largely be broken into two classes. The first measures gravity and celestial mechanics related parameters. Two and three-way coherent doppler measurements are used to study gravity fields of planets as well as search for very low frequency gravitational waves. Two-way ranging measurements to the spacecraft as the spacecraft flies by the target body are used to derive a more accurate orbital ephemeris of that body .

The second class of observations measures the effects of media on the telecommunications signals as they propagate between the earth and spacecraft. The various media probed includes planetary atmospheres, ionospheres, magnetospheres and ring systems as well as interplanetary plasma generated by the sun. A particularly thorough overview and discussion of these propagation experiments is given in **[3]**.

The different experiments each have their own desires and needs. **[4]** discusses three of the experiments which have tended to drive the performance of the ground tracking station and spacecraft oscillator performance. The celestial mechanics experiments are typically operated in the two and three-way coherent doppler modes and utilize the station's clocks for frequency reference. Occultation and some relativity experiments are conducted in the one-way mode and utilize a USO on-board the spacecraft. The USO is used as a reliable frequency reference in the one-way mode when intervening media or solid bodies degrade or block the uplink to the spacecraft. The first such device was implemented on the two Voyager spacecraft and was very much responsible for many of the impressive set of results achieved by the Voyager radio science experiments.

The USO's implemented to date have consisted of a single quartz crystal oscillator operating near 5 MHz which is multiplied to the desired microwave signal frequency (e.g., X-band). The most recent USO's built for Mars Observer and TOPEX have demonstrated performance around one part in 10^{-13} from 1 up to 1000 seconds. These crystal USO's are highly sensitive to the ambient environment and are, as a result, contained in temperature controlled single or dual oven dewars; thermal coefficients can then reach 10^{-12} per degree centigrade. Depending on the mission some USOs must be radiation hardened and some must be shielded against stray magnetic fields generated by adjacent equipment on the spacecraft. Despite the environmental sensitivities, these oscillators are well suited to planetary missions. small, light weight and consume a small amount pf power (primarily for the oven) and have optimum performance (in terms of the Allan deviation) in the 1 to 1000 second regime which is the typical regime of interest for occultation type measurements. Unlike all the other oscillators on a deep space spacecraft, the USO is considered a science payload and is, therefore, designed to less stringent requirements in terms of reliability and redundancy.

REFERENCES:

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[4] E. R. Kursinski, *"Application of High Stability Oscillators to Radio Science Experiments Using Deep Space Probes"*, Proc. of 22nd Annual Precise Time and Time Interval Planning Meeting (PTTI), Dec. 4-6, 1990, pp. 253-263

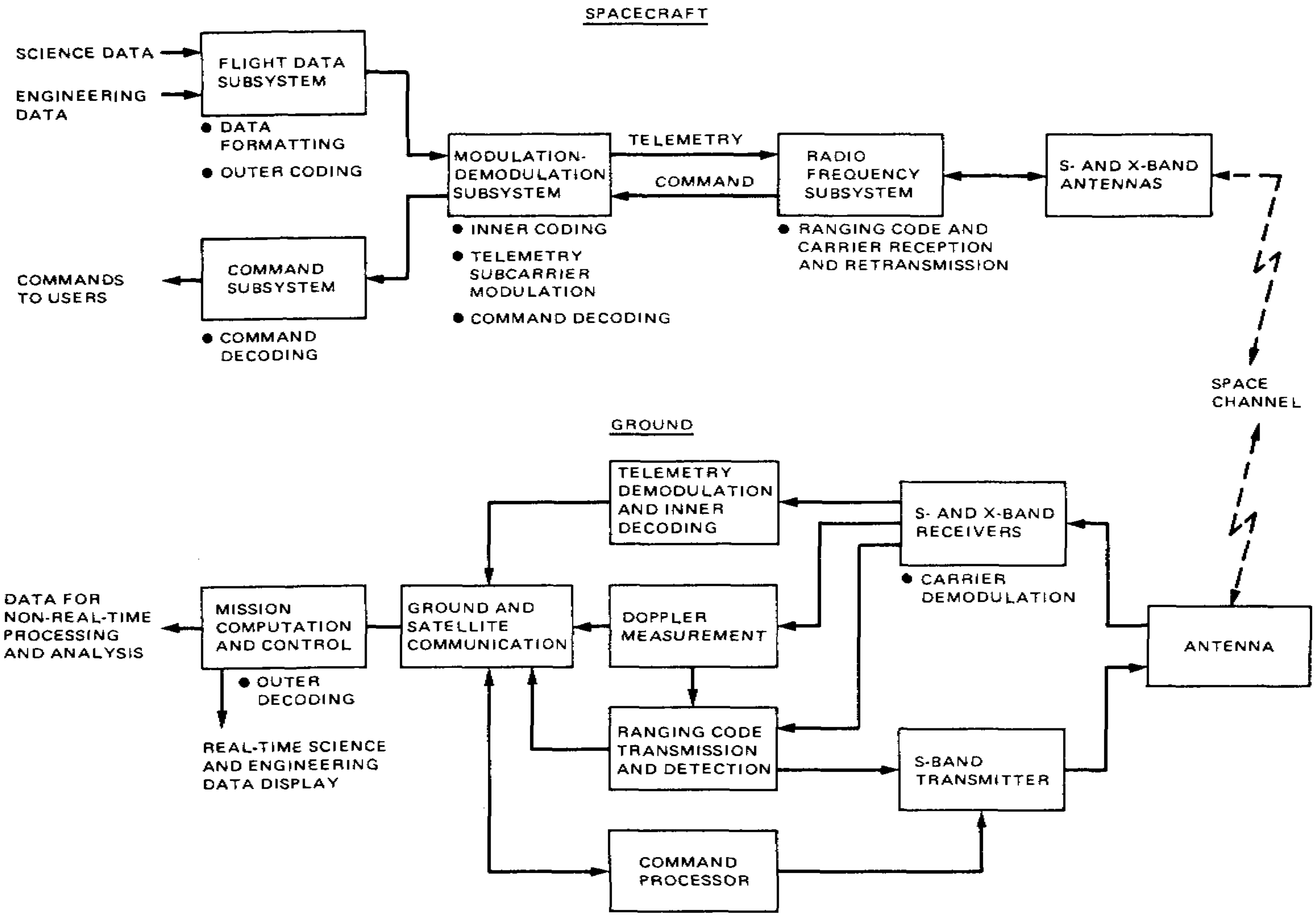

Figure 1: A typical deep space telecommunications system

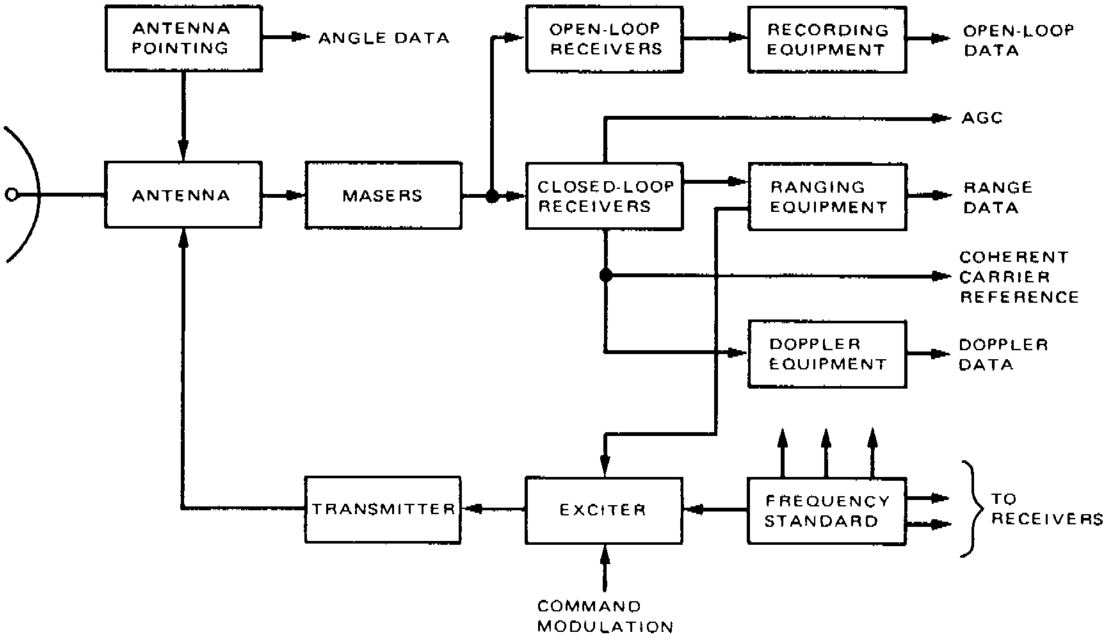

Figure 2: Ground tracking system block diagram

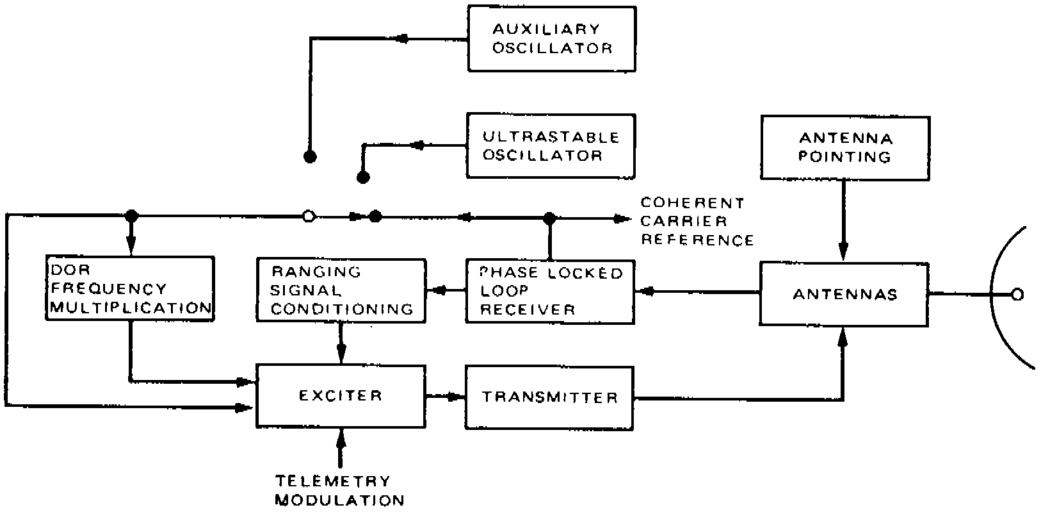

Figure 3: Spacecraft tracking system block diagram

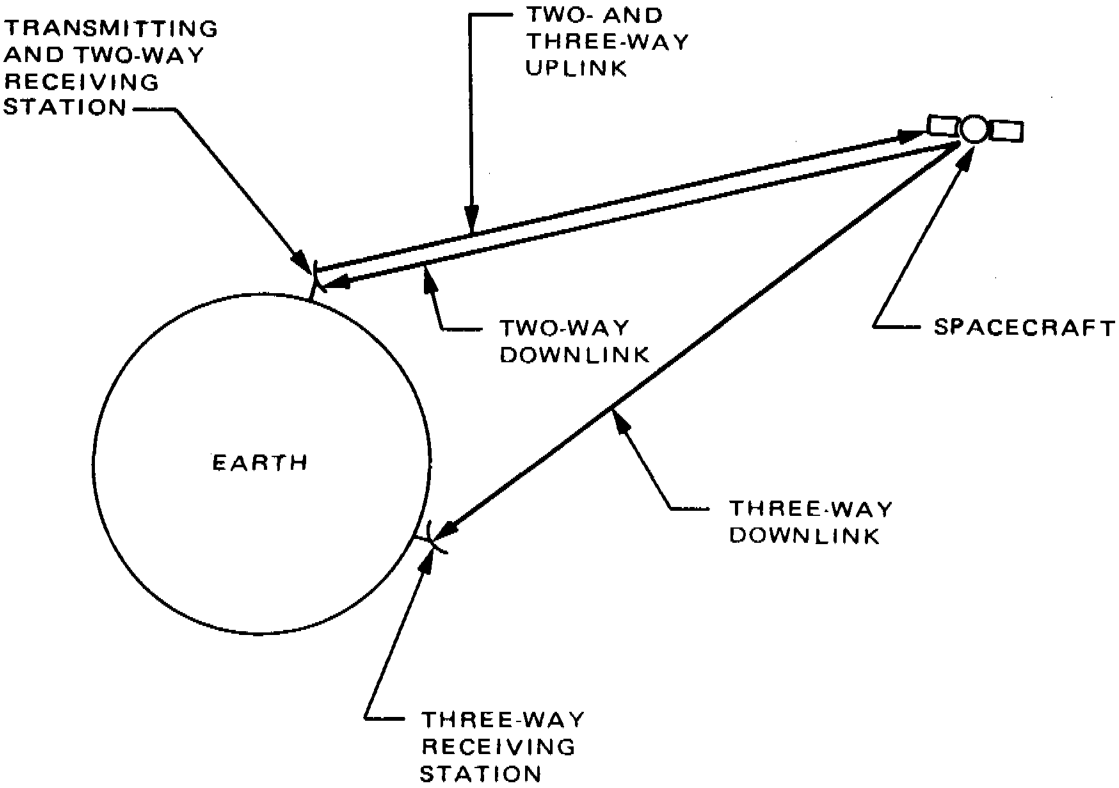

Figure 4: Transmitting and receiving configuration for two- and three-way data

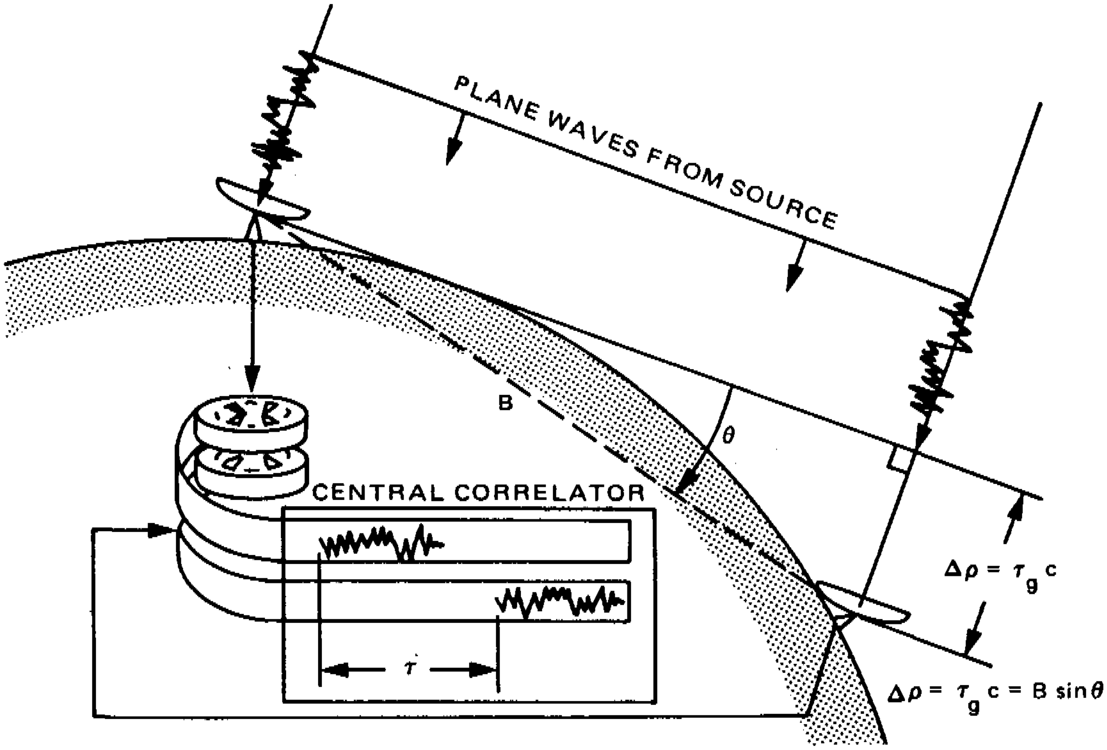

Figure 5: Measuring angular position with VLBI