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PROBING THE EARTH'S GRAVITY FIELD USING SATELLITE-TO-SATELLITE TRACKING (SST)

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GSFC ---- **GODDARD SPACE FLIGHT CENTER**
GREENBELT, MARYLAND

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ABSTRACT

The idea of tracking one spacecraft from another grew out of some tracking
studies performed early in the Apollo program (1962/63). The main practical
advantage of such a technique is that: a) contact time with a low orbiting space-
craft can be increased considerably (approximately 50 minutes vs. 5 minutes for
a single ground station); b) the number of ground stations can be reduced; c) the
dependency on stations on foreign soil can almost be eliminated; and d) detailed
studies of spacecraft motions due to small variations in the earth's gravity field
(anomalies) may be detectable.

This paper describes specifically two Satellite-to-Satellite (SST) tests, namely:
a) the ATS-6/GEOS-3 and b) the ATS-6/Apollo-Soyuz experiment and some of the
results obtained. The main purpose of these two experiments was first to track
via ATS-6 the GEOS-3 as well as the Apollo-Soyuz and to use these tracking
data to determine (a) both orbits, that is, ATS-6, GEOS-3 and/or the Apollo-
Soyuz orbits at the same time; (b) each of these orbits alone and (c) test the
ATS-6/GEOS-3 and/or Apollo-Soyuz SST link to study local gravity anomalies;
and, second, to test communications, command and data transmission from the
ground via ATS-6 to these spacecraft and back again to the ground (Rosman, N.C.)

Most of the interesting data obtained to date originate from the Apollo-Soyuz
Geodynamics Experiment. Thus, it will be discussed in some detail.

Gravity anomalies of say 3 to 5 mgals or larger having wavelength of 500 to
1000 km on the earth's surface are important for studies of the upper layers of
the earth. Such anomalies were actually "seen" for the first time from space
as signatures in the form of very small variation (order of ~1 to 2 cm/s) in the
range rate between ATS-6, GEOS-3 and Apollo-Soyuz. Since the measured range
noise turned out to be only 0.03 to 0.05 cm/s on the average, these signatures
were detected with an excellent signal-to-noise ratio. Orbit determination
examples using SST data from ATS-6 and GEOS-3 are also discussed in detail
together with errors associated with the orbits of GEOS-3. Further, signature
studies and gravity anomaly detections with SST data will be shown and discussed
in detail.

PROBING THE EARTH'S GRAVITY FIELD USING
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INTRODUCTION

Satellite-to-satellite tracking, as well as the transmission of data from one
spacecraft via a synchronous spacecraft back to the ground grew out of the
Apollo program in the earth 1960s. During this time, Goddard was engaged
in the design and construction of the Apollo world-wide tracking network
[Vonbun, 1966]. In studying the early coverage phases of the Apollo, it became
apparent that insertion of the Apollo spacecraft into the earth parking orbit could
unfortunately not be "seen" from any ground station. Thus, it was natural to
look for a ship, aircraft or satellite support for tracking the insertion of the
Apollo spacecraft. Since the idea of satellite-to-satellite tracking was too new
at that time, it was decided to utilize a tracking ship instead to observe the
critical parking orbit insertion phase. Nevertheless, work in this area continued
since it has obvious advantages over the more conventional ground tracking,
namely: (1) A low-orbiting spacecraft can be tracked for a rather long time,
namely, 40 to 50 minutes from a synchronous spacecraft, as compared to only a
few minutes of tracking from an earth station [Vonbun, Mengel, 1968]; (2) the
number of ground stations can be considerably reduced, thus, having quite a
practical and significant impact in cost savings for construction and operations
of ground stations on foreign soil; (3) Orbit determination capability may well
be increased due to relatively long continuing tracking possible with SST tech-
niques; and (4) Finally, probing the earth gravity field anomalies seem to have
a good possibility of success.

In this paper, special emphasis is placed upon a) testing the orbit determination
capability for a low orbiting spacecraft and b) probing the earth gravitational
field using the technique of Satellite-to-Satellite Tracking (SST) [Vonbun, 1972].

It is interesting to note that we are now constructing a Synchronous Orbiting
Tracking Station, namely, the Tracking and Data Relay Satellite System (TDRSS)
to be launched in the 1980/81 time period [NASA/GSFC. 1975].

I. SATELLITE-TO-SATELLITE (SST) PRINCIPLE

The general principle of SST is a rather simple one. In the past fourteen years, all spacecraft tracking operations were performed utilizing ground based electronic or laser tracking systems. In the case of SST one sends, in essence, a tracking station into space, preferably into a very high or synchronous orbit and uses it to track another low orbiting spacecraft [Vonbun, Mengel, 1968]. Obviously, if this can be done, commands as well as data transmission can also be accomplished via the same link. This subject, being that of a communications discipline, will not be further discussed.

A coherent signal is sent from a ground station to ATS-6 turned around there in a phase locked fashion (bent pipe principle) and transmitted to the low orbiting spacecraft. From there the signal is again sent back via the same path to the originating ground station as shown schematically in Fig. 1. Obviously, in order to prevent signal interference, frequency translations have to be made. At the signal originating ground station the outgoing and incoming signals are mixed and the Doppler frequency which is proportionally to $\dot{\rho}_A$ the ATS-6/GEOS-3 or Apollo range rate is then determined with extreme accuracy as shown in Fig. 2. As can be seen, the measured noise of this range rate signal is in the order of only 0.03 cm/s using a 10 sec counting (integration) time to determine the Doppler frequency (or $\dot{\rho}_A$ = 2 × Doppler frequency divided by the wavelength used) [Schmid, et al, 1973; Marini, 1974; Schmid, Vonbun, 1974; Bryan, et al, 1975; Schmid, et al, 1976]. Work on the SST equipment needed for our ATS-6 satellite was started in the 1968/69 time frame, with the ATS-6 and Nimbus-6 spacecraft in mind. The first SST tracking data were obtained from GEOS-3 in April 1974, because of a launch delay of Nimbus-6. Later in this same year, Nimbus-6 and a newcomer for this experiment, namely, Apollo-Soyuz were tracked via ATS-6. Both, range and range rate data are now taken by this method in a routine fashion. Since for the probing of the earth field only range rate information is used because of its extreme sensitivity and precision (fractions of mm/s over ten seconds integration time) the ranging is not to be further discussed. As can be seen from Fig. 1, we are measuring in actuality the total range rate sum $\dot{\rho}$ [Schmid, Vonbun, 1974]. In principle, only the quantity $\dot{\rho}_A$, the range rate between the high and low orbiting spacecraft is of real interest for gravity "probing". The variation of the range rate between the high orbiting spacecraft and the ground can be determined easier since the high orbiting spacecraft does not "follow" the anomalies of the earth gravity field as does the low orbiting spacecraft. This is, in essence, the reason why these anomalies can be "seen" in these range rate signals as will be shown later. A simple analytical expression, in order to get a feeling for the expected gravity anomaly induced variations in the range rate, was published in 1972 for the ATS-F/Nimbus-E case [Vonbun, 1972].

II. ORBITAL ERROR ESTIMATES

For all our advanced geodynamics work in connection with NASA's Earth and Ocean Dynamics Program (EODAP) [NASA, CR-1579, 1970; Vonbun, 1972; Vonbun 1975/76] orbital uncertainties due to errors in the tracking system or errors in the Earth's gravitational field are of importance. It is, however, quite difficult to really establish orbital errors and separate their sources. One attempt has been suggested by J. Siry, namely, to compute orbital arcs that "overlap" and determine their differences in the overlapping region. If one could determine an orbit perfectly, the overlap difference should be zero. Being finite, however, gives some indication of the orbit errors. These errors stem from the tracking and Earth's gravity field errors and not from computational ones [Siry, Steward, 1969; Vonbun, 1970]. Figure 3 depicts orbital overlap arcs for GEOS-3 when all available tracking data for both, the ATS-6 as well as the GEOS-3 spacecraft are used. In this case both orbits, that is, all 12 orbital parameters, were determined simultaneously using the Goddard Earth Model (GEM-7) [Lerch, 1976]. The tracking data and their intervals together with overlap regions #1 and #2 are also shown. Obviously, the more tracking data, the "better" the orbits are determined. Figures 4 and 5 clearly show this fact depicting the orbital uncertainties for GEOS-3 only, the near earth spacecraft of special interest. If a good tracking coverage can be achieved (overlap #2) the uncertainties are reasonably small as can be seen from Figure 5. It is also interesting to note that the radial and cross track errors zero out as predicted over a longer time than the orbital period of say 5 to 10 hours [Bonavito, 1975]. In case only SST data are used for the determination of the GEOS-3 orbit, the uncertainties are as expected somewhat larger as shown in Figure 6. Please note, however, that in this case the ATS-6 orbit has been determined separately by using a trilateration tracking scheme [Schmid, et al, 1976]. Here one ground station (Rosman, N.C.) and two transponders measuring range and range rate (Mojave, California and Santiago, Chile) have been used for the ATS-6 orbit computations. Simultaneous accurate range and range rate measurements from three points give, of course, quite a "good" solution.

III. SST GRAVITY ANOMALY DETECTION

As mentioned before, one of the major advantages of the SST technique [Vonbun, 1972 and 1975] is the detection and hopeful solution of gravity anomalies of rather short wavelength, say in the order of 500 to 1000 km or so. To solve for this kind of gravity anomalies using the conventional global spherical harmonics series expansion of the Earth's gravity field seems to be quite impossible. Expansions to order and degree of about 40 to 80 or so would be needed, which is quite a difficult task even with today's large computers such as the IBM 360-95

or CDC 6600, for instance. Figure 7 depicts a "computed" range rate variation for a $4° \times 4°$, 5 mgal anomaly [Vonbun, 1972] and Figures 8 and 9 show detected anomalies from the range rate data of the recent Apollo-Soyuz/ATS-6 Geo-dynamics Experiment [Vonbun, et al, 1976]. Similar "range rate signatures" have been obtained from many other parts of the globe. Areas where our present knowledge is rather sparse such as most of the part of the southern hemisphere. Never before have "local" anomalies of this kind been detected using satellite methods. The signatures as shown were obtained by subtracting the "computed" range rate $\dot{\rho}_{Ac}$ between the high and low orbiting spacecraft using the GEM-1 or GEM-7 gravity field, respectively, and the "measured" $\dot{\rho}_{Am}$ as obtained from the experiment. Since these fields do not model these rather local anomalies, they became as can be seen quite pronounced in this process $[(\dot{\rho}_A \text{ comp} - \dot{\rho}_A \text{ meas}) = \Delta\dot{\rho}_A$, the range rate variation]. The fact that the experimental obtained range rate noise values are very small as shown in Figure 2 and that the signatures are repeatable orbit by orbit rules almost any other sources out which could preduce such range rate variations.

Another example which demonstrates that strong gravity information is contained in the SST data is depicted in Fig. 10. In this case, very good GEOS-3 orbits using all available tracking data (see also Fig. 3) have been computed using two different gravity fields, namely, GEM-1 and GEM-7, a more advanced field model. From these, the difference in the measured range rate data (due to the difference in the fields) have been computed and plotted in Fig. 10 (points). The theoretical or computed affect of these two fields is also shown (solid line). The agreement, as can be seen, is quite good indicating that these values do result from the difference of two gravity field models as mentioned.

Our next and most important task lies still ahead, namely, to compute the anomalies on the ground (under or near under the orbital track) based upon these range rate variations [Vonbun, et al, 1976]. Preliminary results indicate that this may indeed be possible. Recently, we were able to compute an anomaly, to quote one example, and reduce the range rate signate considerably when this so com-puted anomaly was added to the local gravity field of the earth. This is but only one example at this time. A major effort is now underway at Goddard to do just that. For this purpose we have to use, however, all the data from all 120 orbital arcs we collected during the Apollo experiment which are not yet available.

IV. CONCLUSIONS

In conclusion, it can be stated that it is possible using SST data to perform satis-factory orbital computations for most spacecraft. It seems to indicate, however, that ultraprecision orbits of low orbiting satellites (errors in dm range) cannot

be obtained from using a "tracking spacecraft" in a geosynchronous orbit. A better geometry and possibly up to three spacecraft may be needed for this purpose with different inclinations (0°, 45°, 90°) and orbital periods of 10 to 20 hours.

It can, however, be stated that local gravity anomalies can be detected and thus compared to those known from other measurements. This in turn may be used for testing presently known anomalies on a global scale.

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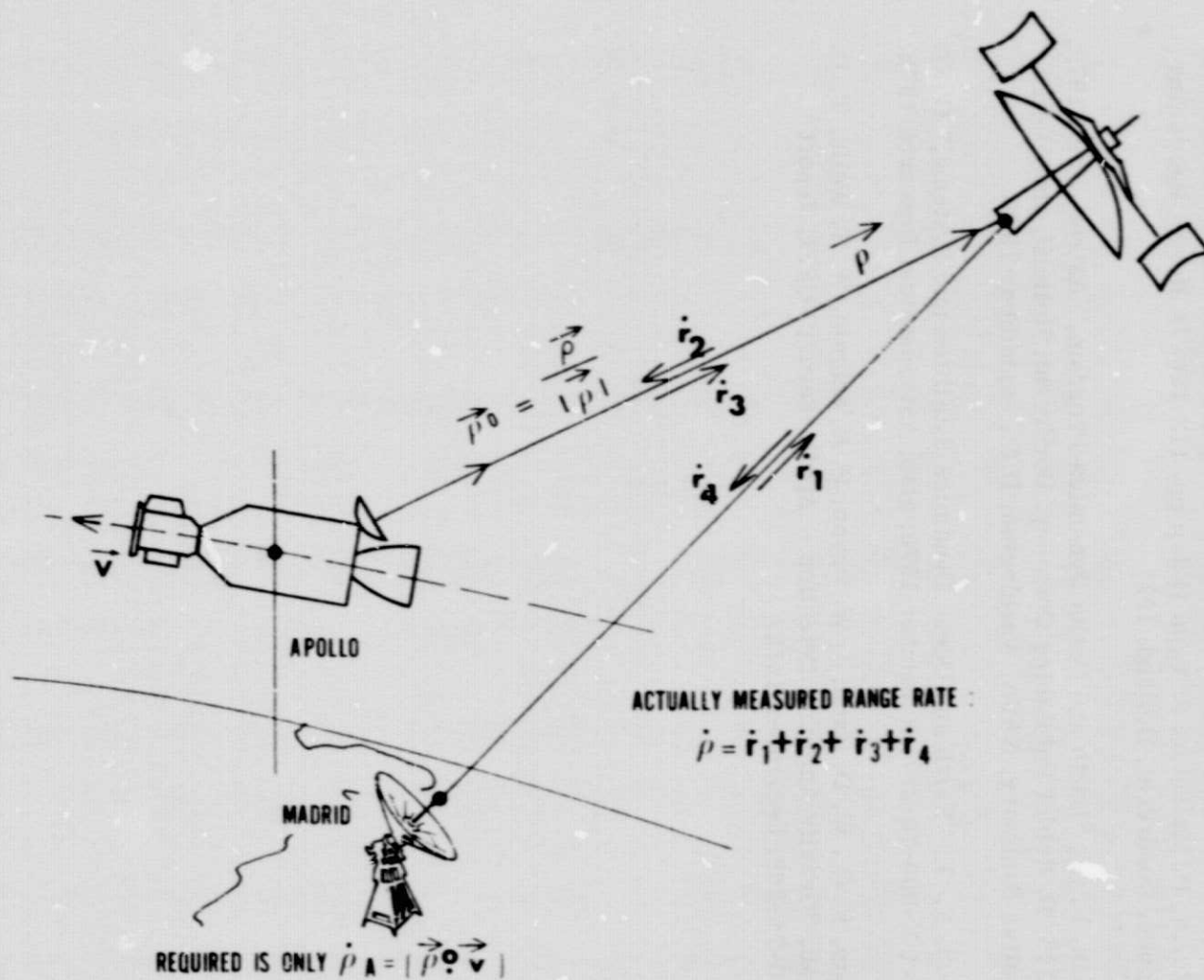
Figure 1. Range Rate Measurements Schematic for ATS-6 and Apollo
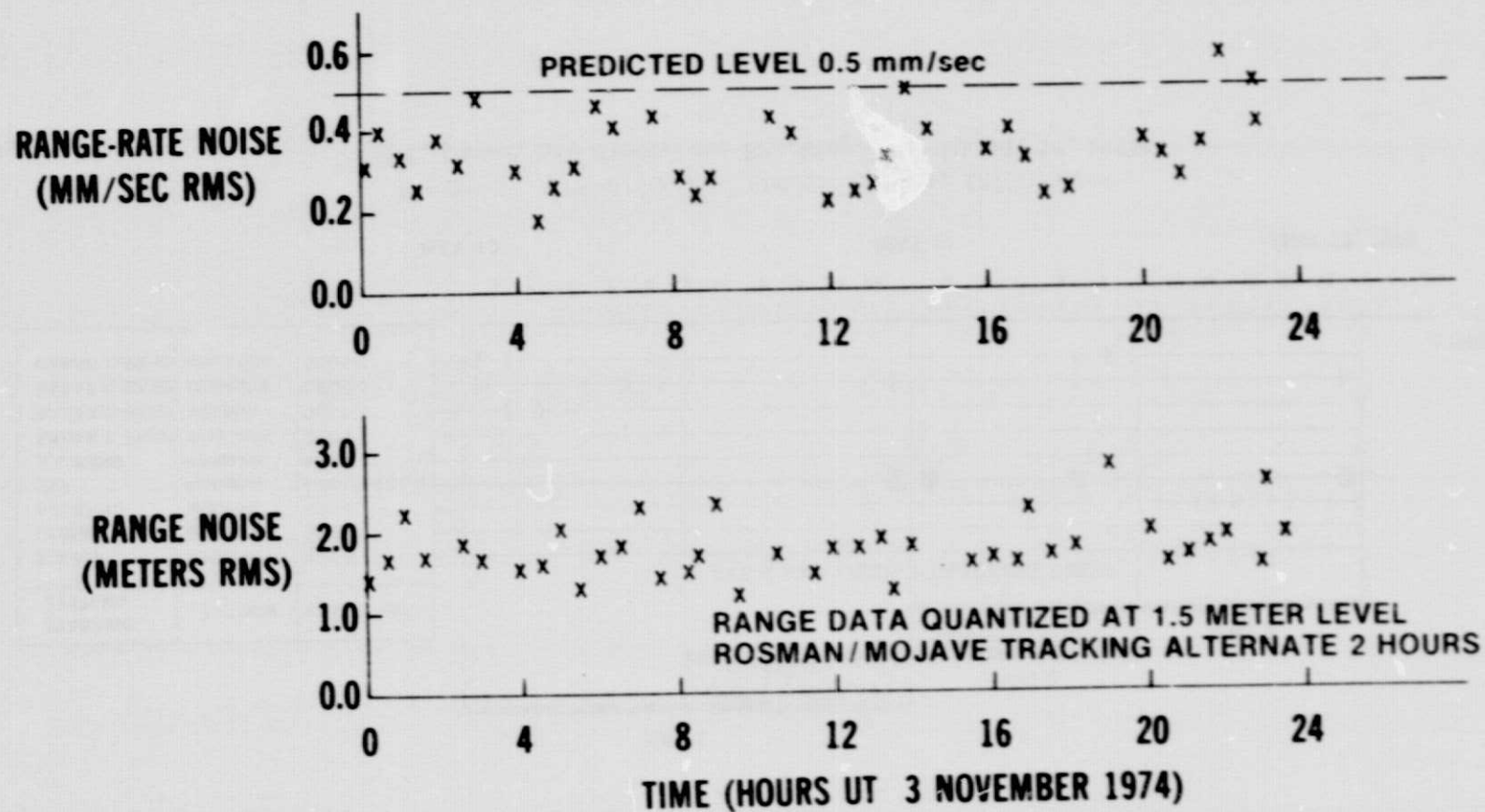
Figure 2. Tracking System Noise

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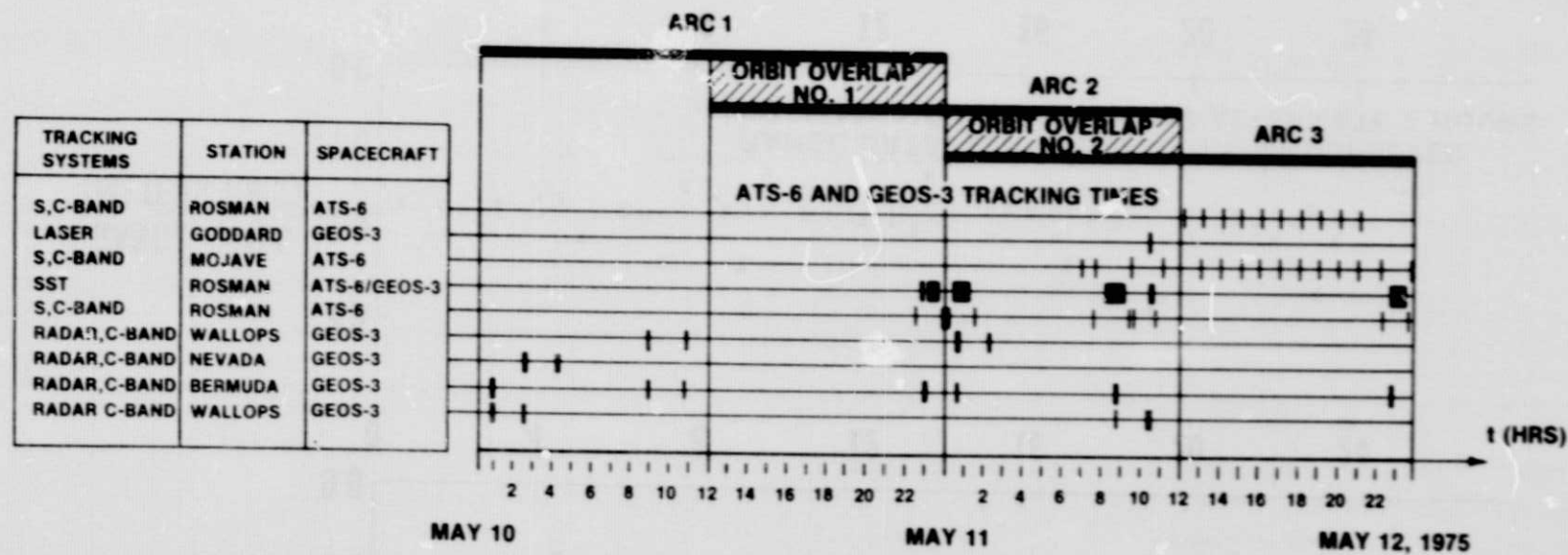
Figure 3. ATS-6/GEOS-3 Orbital Overlap Differences
(SST, Laser, and Electronic Tracking, May 10, 11, 12, 1975)
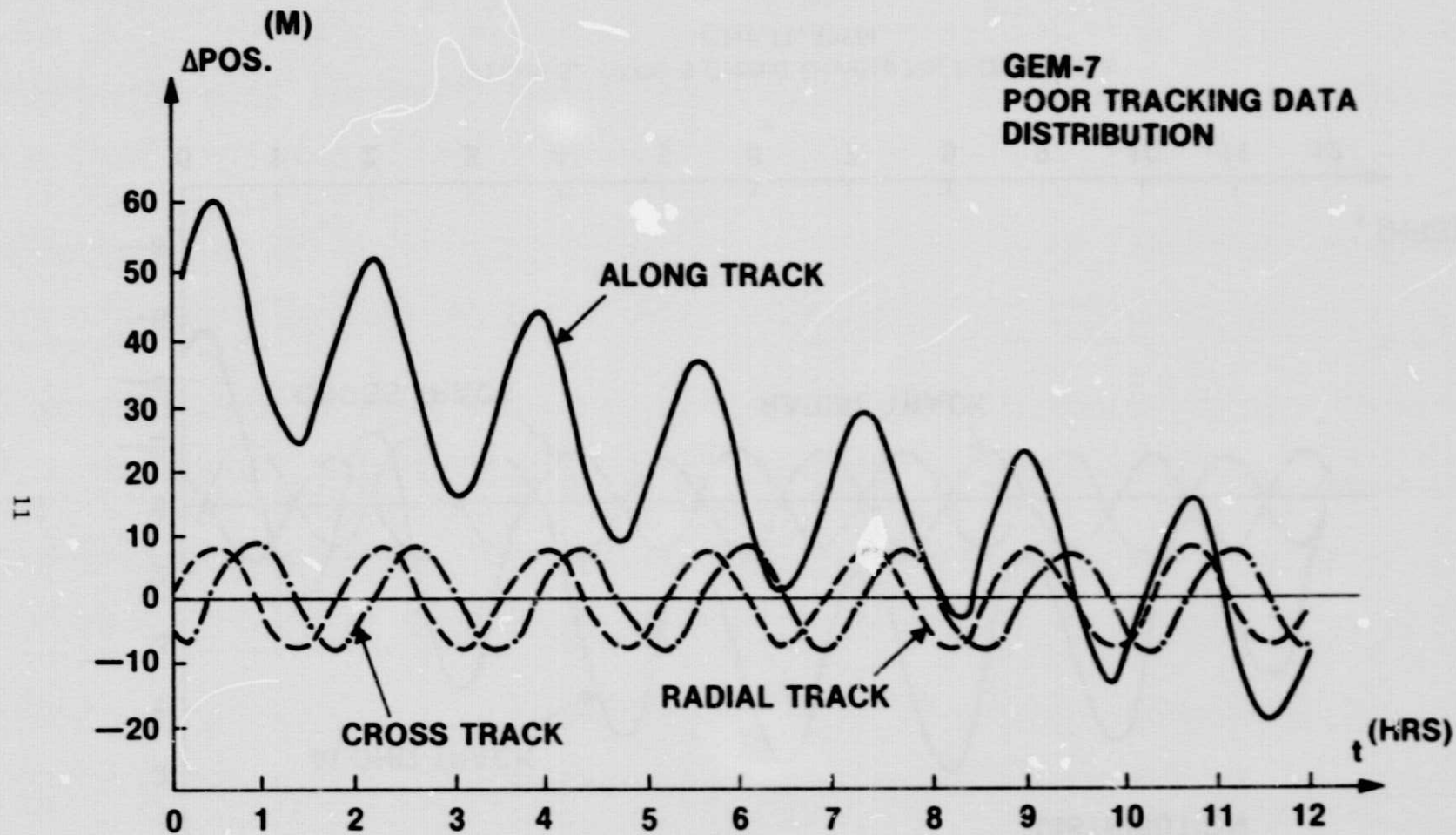
Figure 4. GEOS-3 Orbital Overlap No. 1 Differences (May 10, 1975)
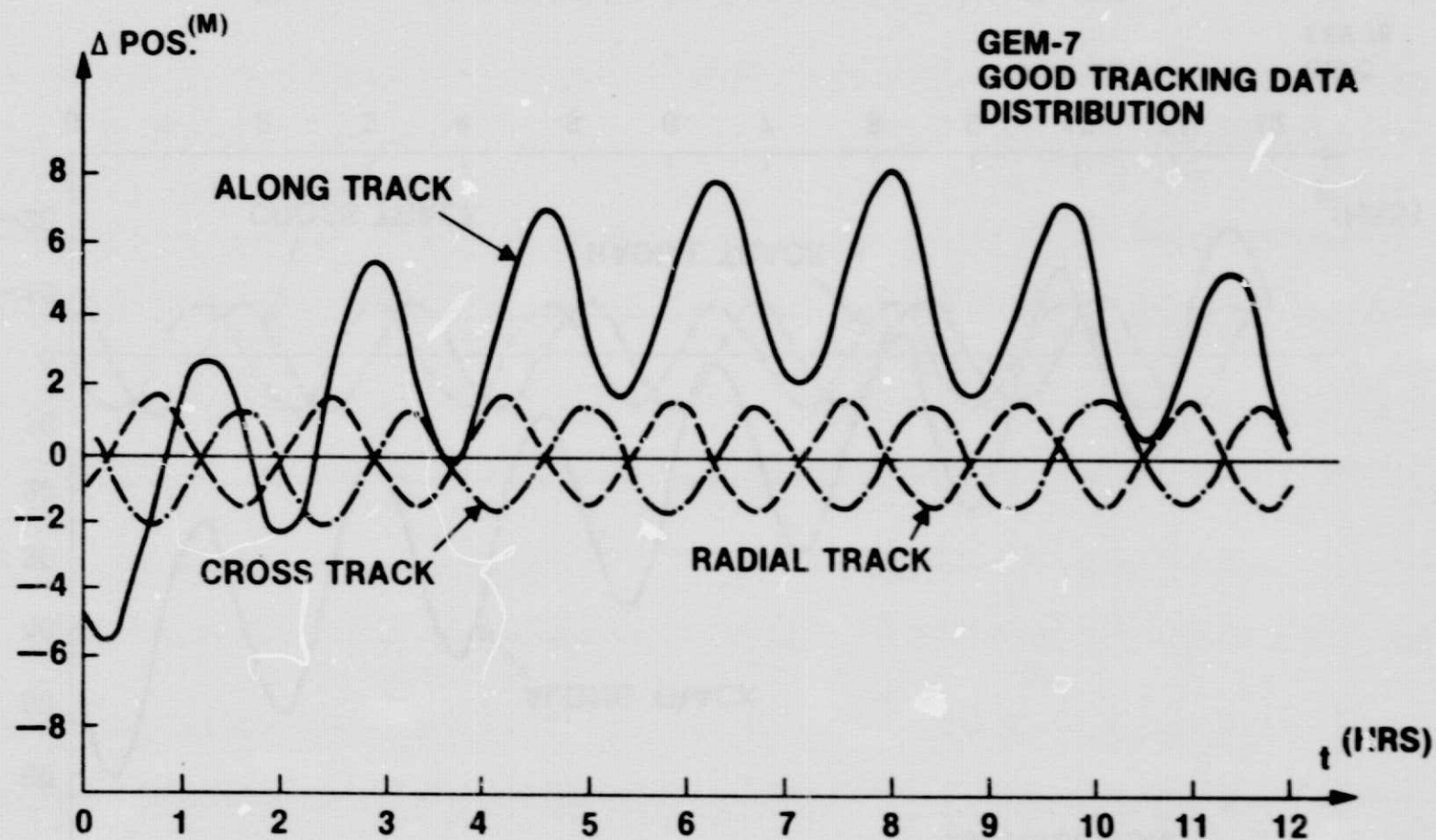
Figure 5. GEOS-3 Orbital Overlap No. 2 Differences
(May 11, 1975)

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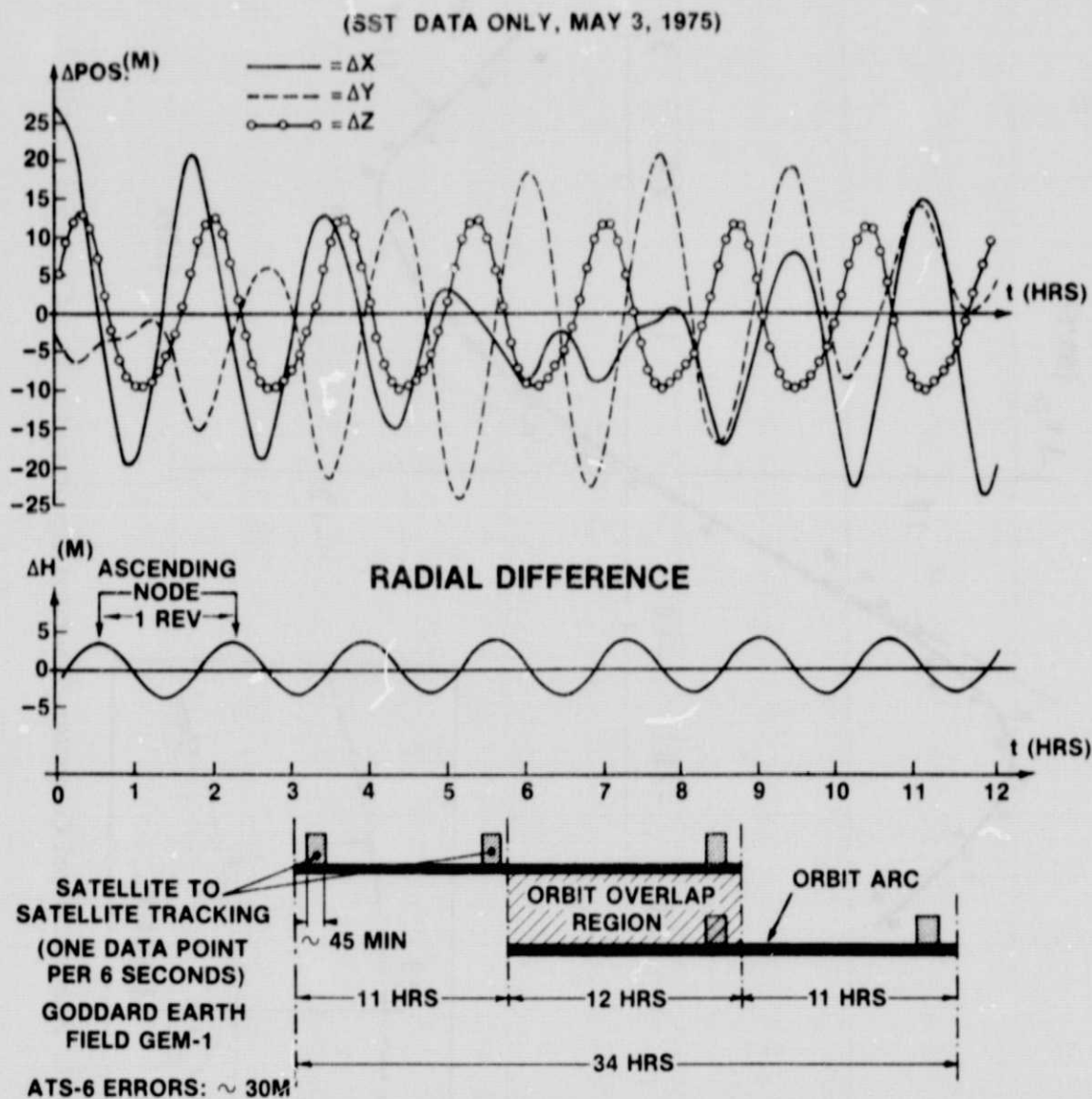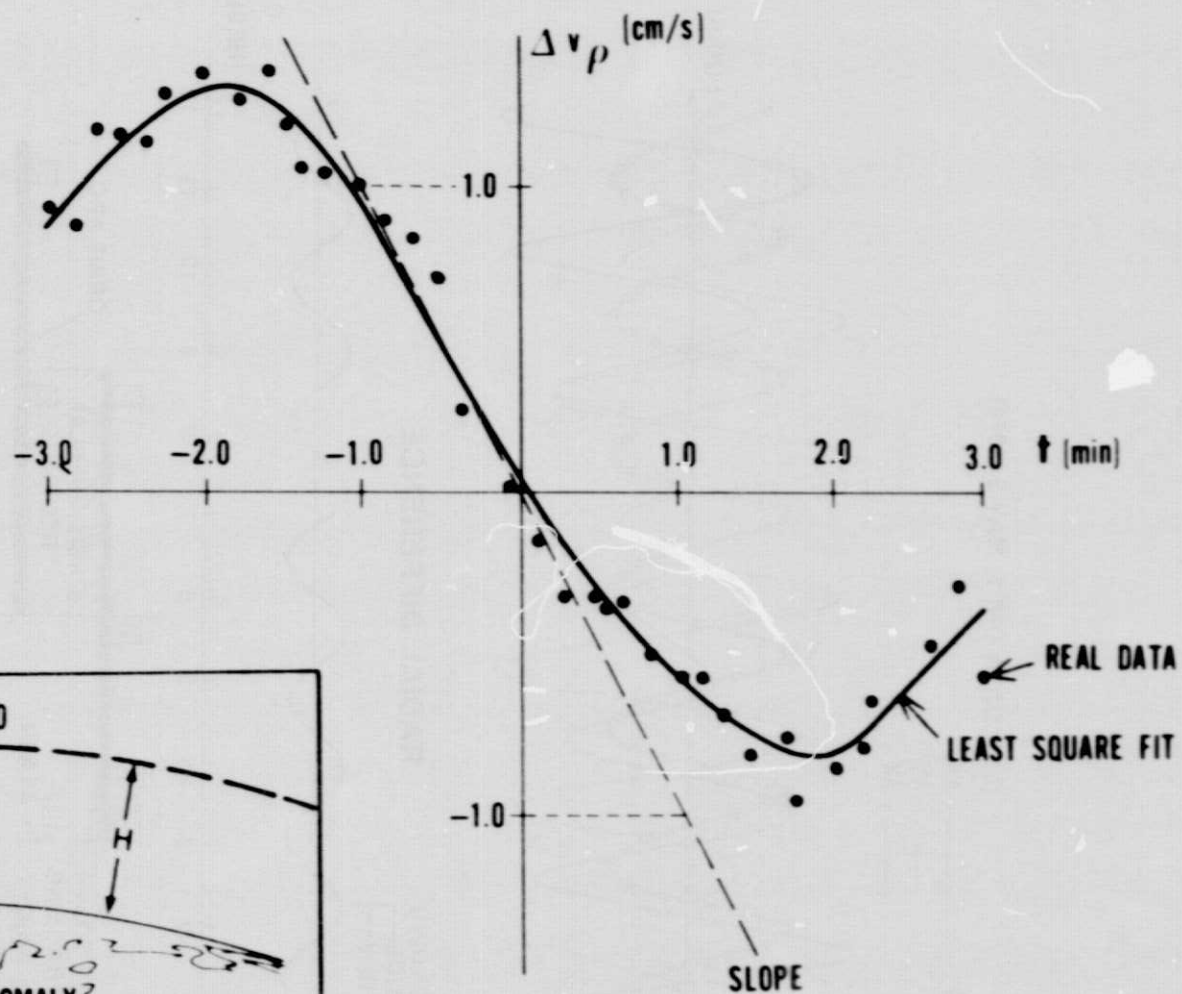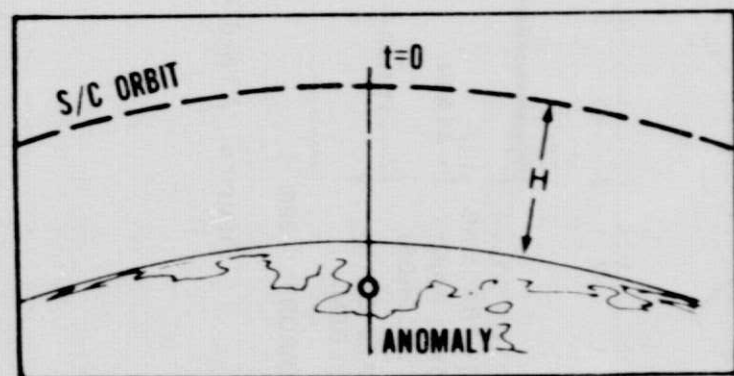Figure 6. ATS-6/GEOS-3 Orbital Overlap Differences

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Figure 7. Analytical and Computer Simulated Signature for $4° \times 4°$ 5 mgal Gravity Anomaly
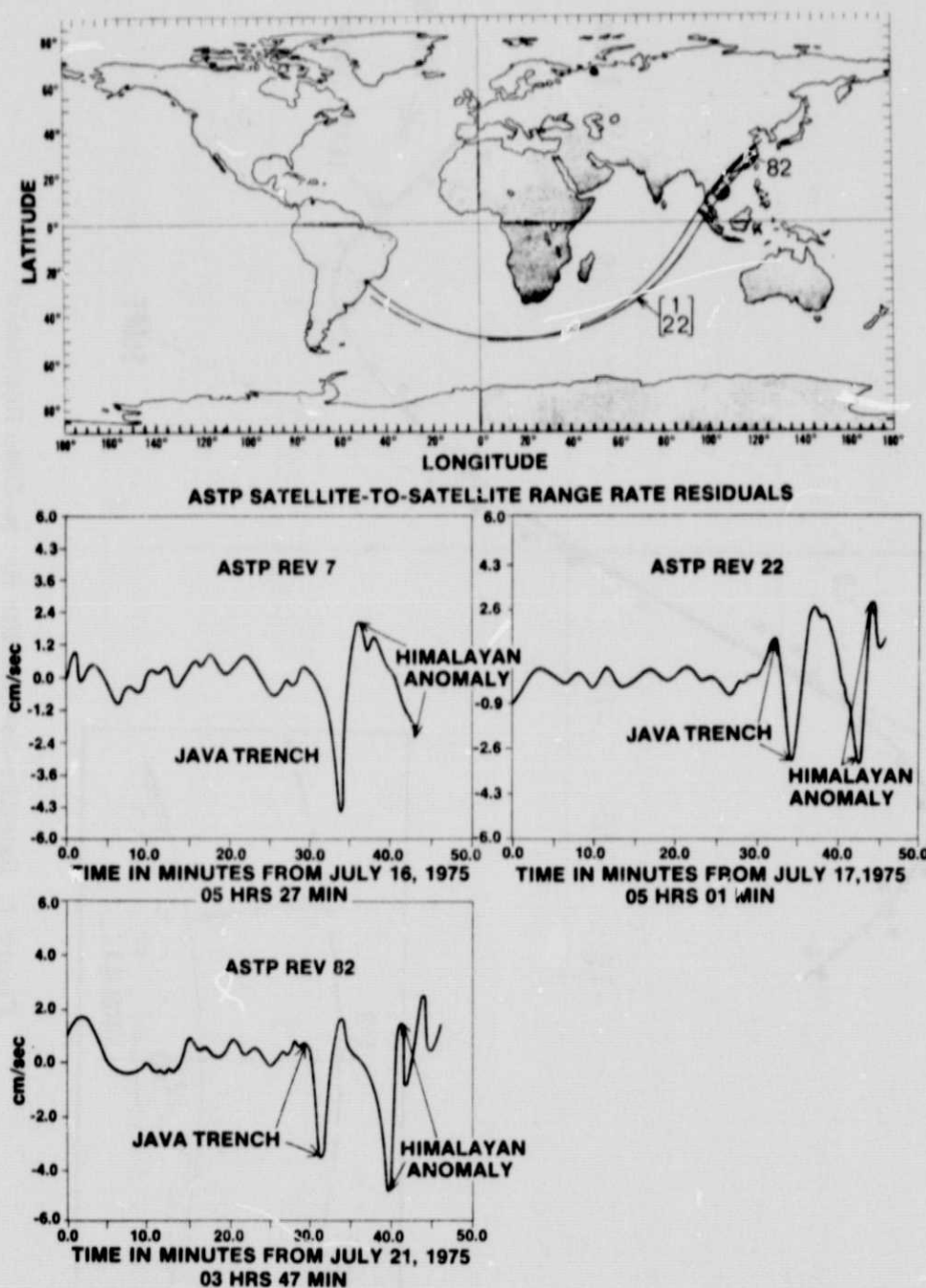
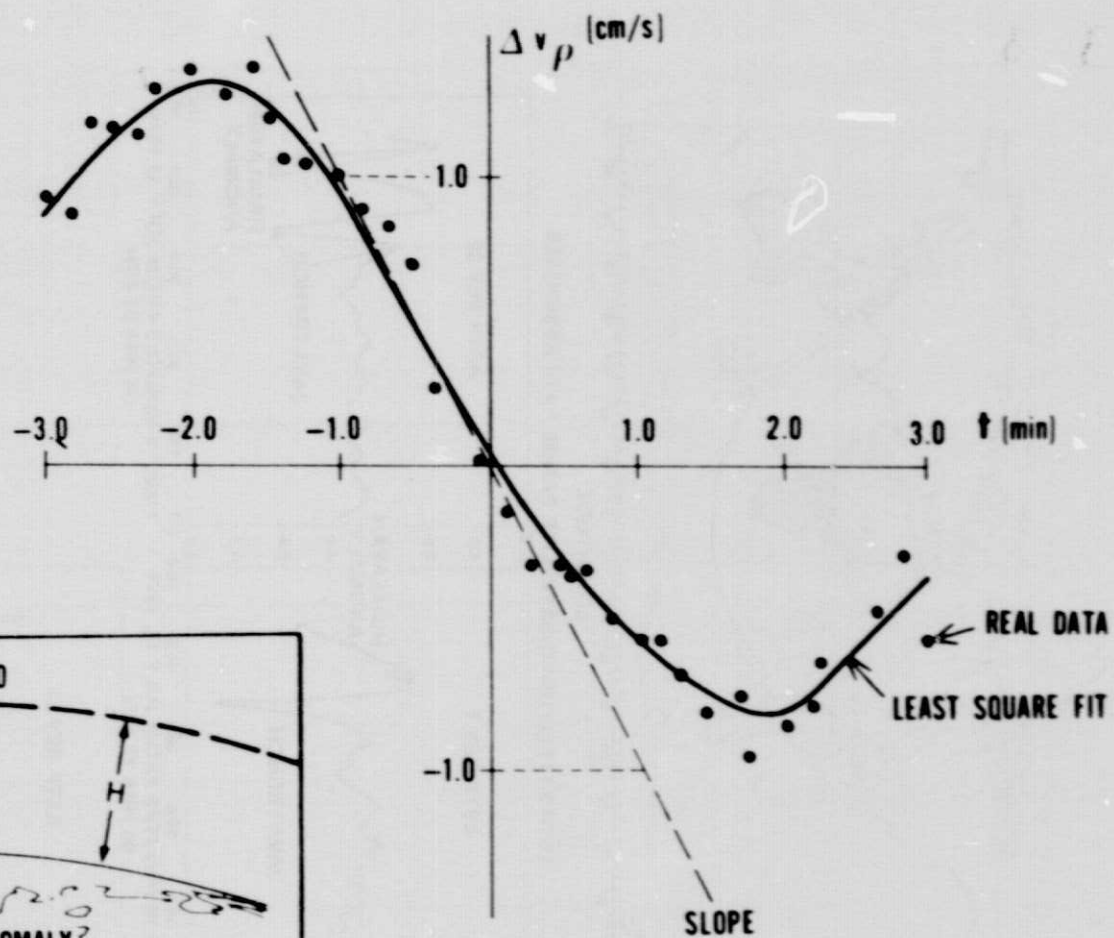Figure 8. Range Rate Signatures of ASTP Revolutions
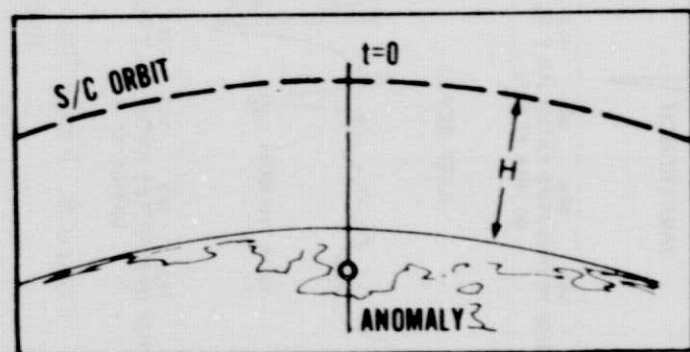in the Same Area

Figure 9. Satellite-to-Satellite Range-Rate Residuals
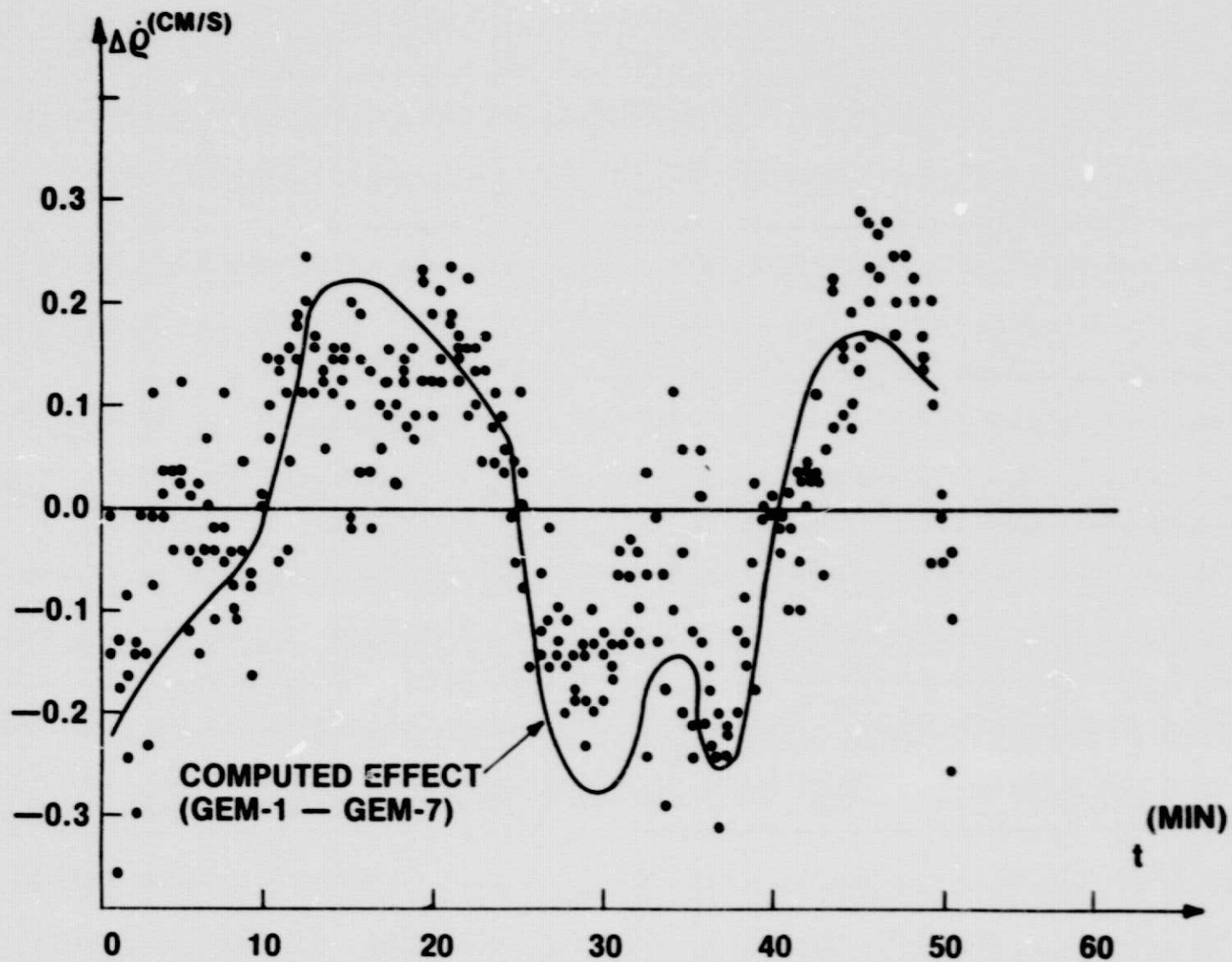Revolution 115 (GEM-1 Geopotential)

Figure 10. ATS-6/GEOS-3 Range-Rate Differences
(GEM-1, GEM-7)