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Probing the Earth's gravity field by means of satellite-to-satellite tracking

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The idea of tracking one spacecraft from another grew out of some tracking studies performed early in the Apollo programme (1962–3). The main practical advantage of such a technique is that (*a*) contact time with a low orbiting spacecraft can be increased considerably (approximately 50 min *v.* 5 min 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 tracking (s.s.t.) 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 s.s.t. 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 3–5 mGal ($3–5 \times 10^{-5}$ m s^{-2}) or larger having wavelength of 500–1000 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 0.03–0.05 cm/s on the average, these signatures were detected with an excellent signal-to-noise ratio. Orbit determination examples using s.s.t. 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 s.s.t. data will be shown and discussed in detail.

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 Space Flight Center 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, 40–50 min 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 s.s.t. techniques; and (4) finally, probing the Earth gravity field anomalies seems 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 by using the technique of satellite-to-satellite tracking (s.s.t.) (Vonbun 1972).

It is interesting to note that we are now constructing a synchronous orbiting tracking station, namely the Tracking and Data Relay Satellite (TDRS) to be launched in the 1980/1 time period (Vonbun & Mengel 1968; NASA/GSFC, 1969).

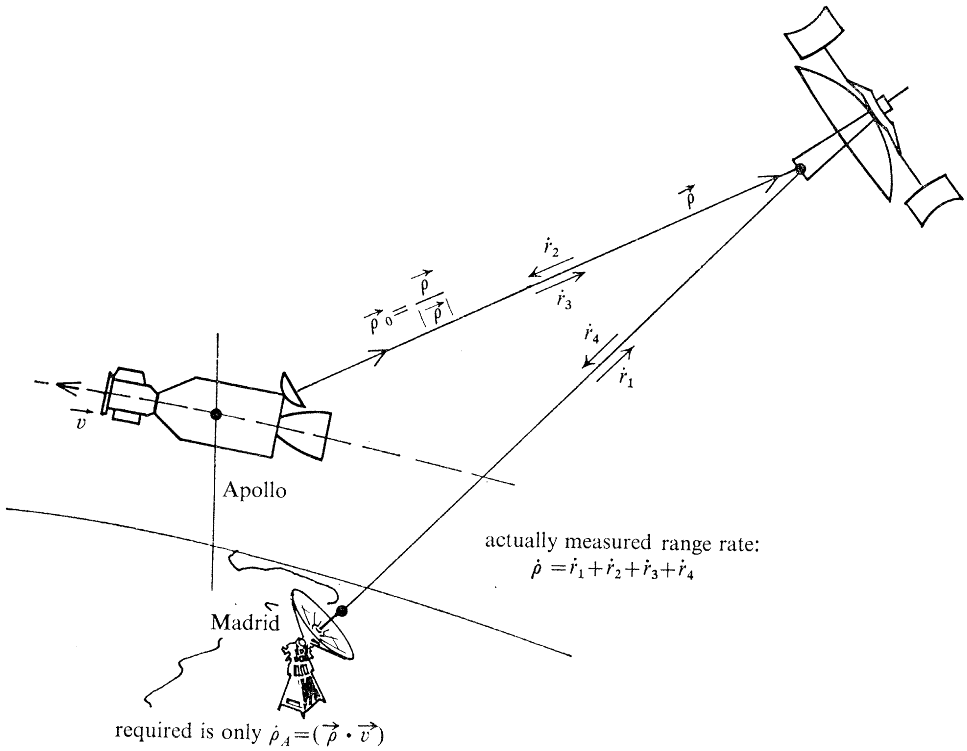

FIGURE 1. Range rate measurements schematic for ATS-6 and Apollo.

1. SATELLITE-TO-SATELLITE PRINCIPLE

The general principle of s.s.t. is a rather simple one. In the past 14 years, all spacecraft tracking operations were performed utilizing ground-based electronic or laser tracking systems. In the case of s.s.t. 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 figure 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 figure 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 s counting (integration) time to determine the Doppler frequency (or $\dot{\rho}_A = 2 \times$ Doppler frequency divided by the wavelength used) (Schmid *et al.* 1973; Marini 1974; Schmid & Vonbun 1974; Bryan *et al.* 1975; Schmid, Argentiero & Vonbun 1976). Work on the s.s.t. equipment needed for our ATS-6 satellite was started in the 1968/9 time frame, with the ATS-6 and Nimbus-6 spacecraft in mind. The first s.s.t. tracking data were obtained from Geos-3 in April 1974, because of a launch delay of Nimbus-6.

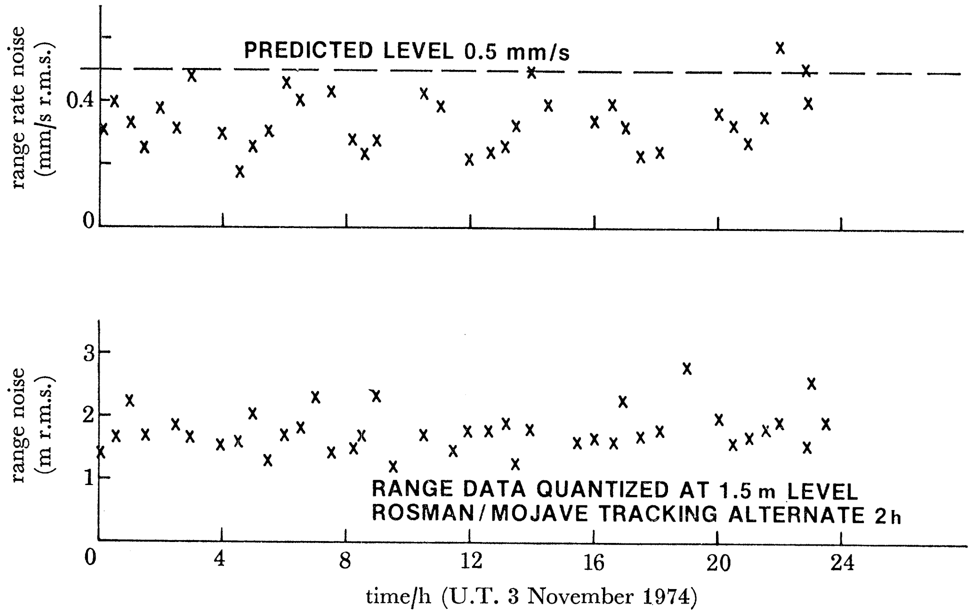

FIGURE 2. Tracking system noise.

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 millimetres per second over 10 s integration time) the ranging is not to be further discussed. As can be seen from figure 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 more easily 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).

2. Orbital error estimates

For all our advanced geodynamics work in connection with N.A.S.A.s Earth and ocean dynamics program (N.A.S.A. CR-1579 1970; Vonbun 1972; Vonbun 1975) orbital uncertainties due to errors in the tracking system and 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,

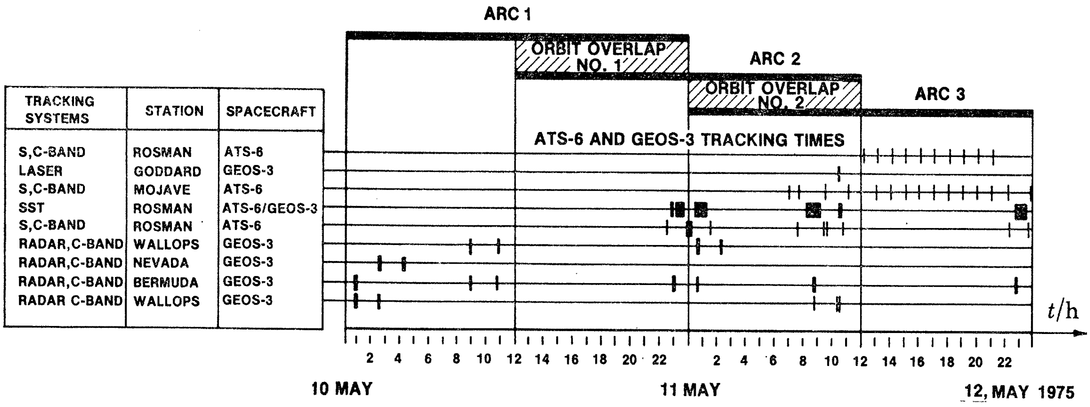

Figure 3. ATS-6/Geos-3 orbital overlap differences (s.s.t., laser and electronic tracking, 10–12 May 1975).

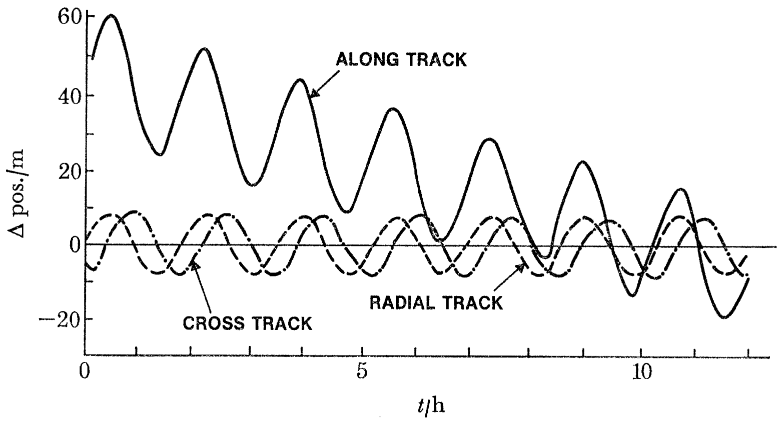

Figure 4. Geos-3 orbital overlap no. 1 differences (10 May 1975).

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 1971). 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 5–10 h (Bonavito 1975). In case only s.s.t. 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,

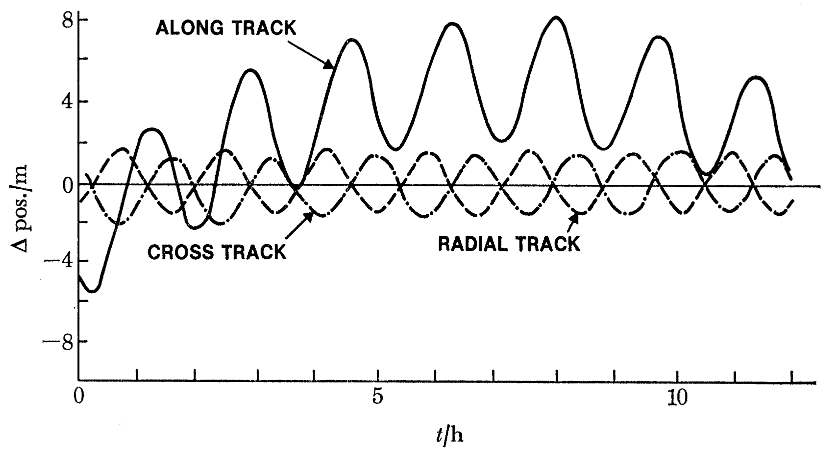

FIGURE 5. Geos-3 orbital overlap no. 2 differences (11 May 1975).

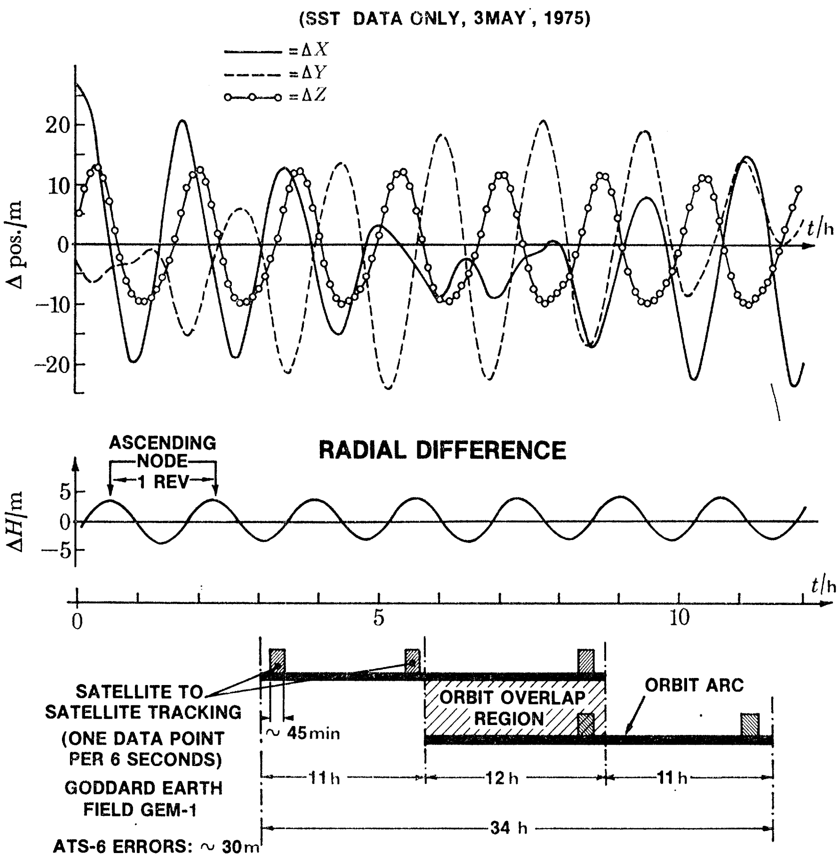

FIGURE 6. ATS-6/Geos-3 orbital overlap differences.

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.

3. S.s.t. gravity anomaly detection

As mentioned before, one of the major advantages of the s.s.t. technique (Vonbun 1972, 1975) is the detection and hopeful solution of gravity anomalies of rather short wavelength, say in the order of 500–1000 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 40–80 or so would be needed, which is quite a

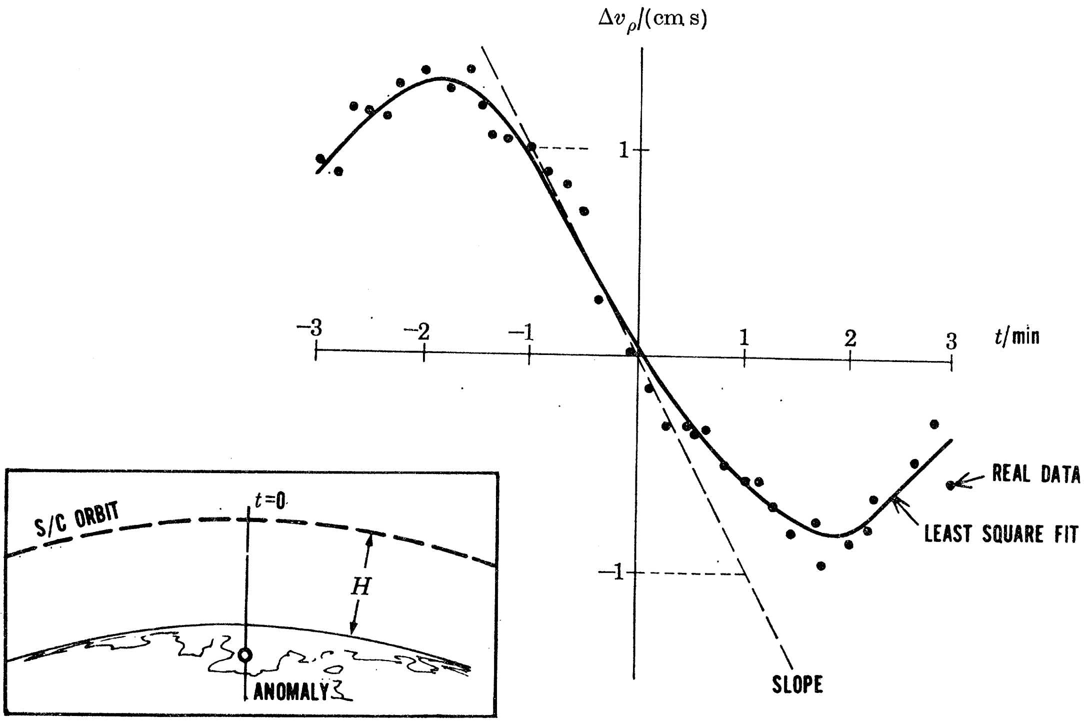

Figure 7. Analytical and computer simulated signature for 4° × 4° 5 mGal gravity anomaly.

difficult task even with today's large computers such as the IBM360-95 or CDC 6600, for instance. Figure 7 depicts a 'computed' range rate variation for a 4° × 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 geodynamics 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 by 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 [$(\dot{\rho}_{Ac} - \dot{\rho}_{Am}) = \Delta\dot{\rho}_A$, 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 produce such range rate variations.

Another example which demonstrates that strong gravity information is contained in the s.s.t. data is depicted in figure 10. In this case, very good Geos-3 orbits using all available tracking data (see also figure 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 figure 10 (points). The theoretical or computed effect 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.

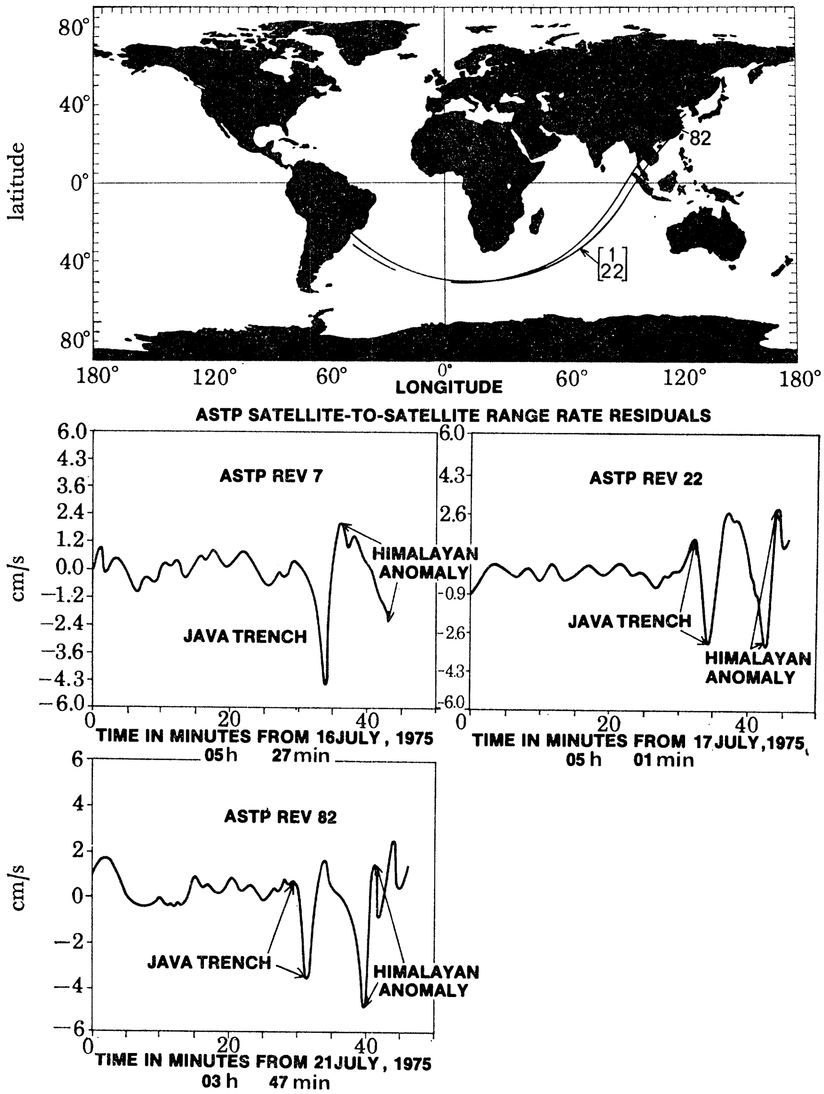

FIGURE 8. Range rate signatures of ASTP revolutions in the same area.

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 computed 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 G.S.F.C. 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.

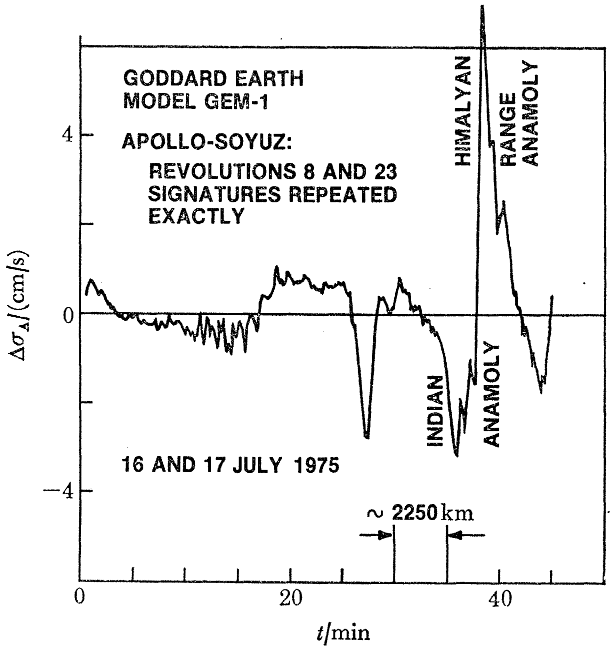

FIGURE 9. Apollo-Soyuz s.s.t.-range rate residuals.

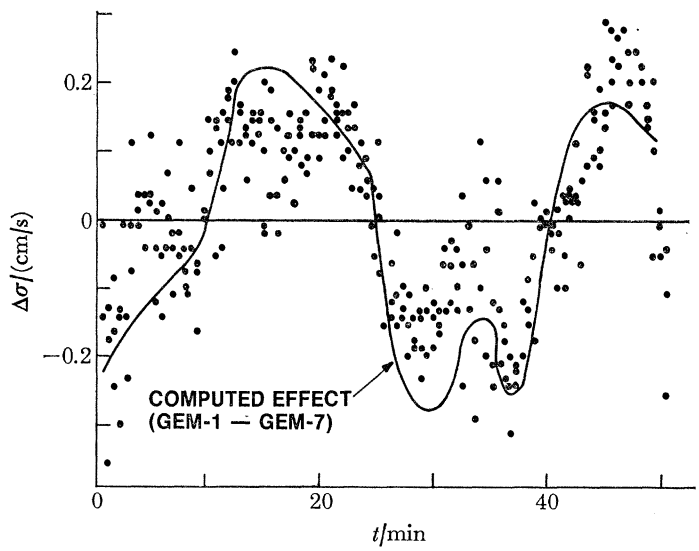

FIGURE 10. ATS-6/Geos-3 range rate differences (GEM-1, GEM-7).

4. CONCLUSIONS

In conclusion, it can be stated that it is possible by using s.s.t. data to perform satisfactory 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 10–20 h.

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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