SVN49 and Other GPS Anomalies

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Elevation-Dependent Pseudorange Errors in Block IIRs and IIR-Ms

An investigation into the elevation-dependent pseudoranging anomaly on the most recently launched GPS satellite has led to discovery of similar, but much smaller anomalies on other spacecraft. A pair of European GNSS experts describe the behavior of these satellites as well as results of initial efforts by the U.S. Air Force to correct the anomaly.

The GPS spacecraft SVN49 (Space Vehicle Number 49), also known as Block IIR-20(M) and PRN01, carries the demonstration payload for the new civil GPS L5 signal. Its March 24, 2009, launch enabled the United States to meet the International Telecommunications Union (ITU) deadline for securing primary rights to use of the RF band by GPS.

However, a report on SVN49 presented by the GPS Wing's chief engineer, Lt. Col. David Goldstein to the European Navigation Conference in Naples, Italy, on May 4 mixed good news with bad.

The demonstration L5 signal began transmitting successfully on April 10. However, other GPS signals being broadcast by the satellite — particularly those at the L1 frequency — demonstrated larger than expected pseudorange errors that appear to be elevation-dependent. That is, they change with the varying elevation angle of the satellite as it rises and sets in the sky.

These signal anomalies, characterized by the U.S. Air Force as "out of family" transmissions, has kept the latest GPS satellite from being declared healthy.

The cause of the SVN49 anomaly, which appears most strongly on signals transmitted on the L1 frequency, is now understood, as well as the reason why certain receivers do not "see" the anomaly. The effect is caused by signal reflections coming from a special auxiliary port (designated J2) that is used to feed the L5 signal to the satellite's antenna array.

These reflections cause a secondary-path signal with a delay of approximately 30 nanoseconds, which has the appearance of a multipath error. Ground receivers with advanced multipath mitigation techniques are not as sensitive to the anomaly — or at least much less so.

In the course of our investigations into the signal anomaly on SVN49, we learned that GPS SVN55 and, most likely, other Block IIR and IIR-M satellites carry some electronic equipment connected to the same auxiliary port as used for the L5 signals on SVN49.

(*Editor's Note:* Independent sources have confirmed to *Inside GNSS* that a classified payload has been connected to the J2 port on several satellites. However, unlike SVN49, these classified packages include a component designed to negate or dampen the secondary-path signal.)

Assuming that any electronic signal connected to this auxiliary port would likely cause a similar kind of signal reflection — and associated disturbance in pseudorange accuracies as observed on SVN49, we took a closer look at the residuals of all GNSS satellites used in ESOC's routine processing of observations for the International GNSS Service (IGS).

Our analysis revealed that SVN49-like L1 pseudorange anomalies are indeed present on several GPS Block IIR and IIR-M satellites, but these anomalies are much smaller in size.

U.S. Air Force operators are making a substantial effort to mitigate the anomaly on SVN49. Their initial effort involved significantly changing the broadcast ephemerides of this satellite, that is, the information transmitted regarding the satellite orbit and clock.

These alterations further complicate the handling of this satellite. The surprising fact here was that the changes in the broadcast ephemerides were of the level of ~150 meter whereas the reported signal problems were at the few meter level only.

In this article we take a detailed look at the signal anomaly observed for SVN49 and other satellites and at the quality and "treatment" of broadcast ephemerides and time being undertaken to mitigate the effects of the signal anomaly.

Analysis

As one of the International GNSS Service (IGS) analysis centers, the European Space Operations Centre (ESOC) in Darmstadt, Germany, routinely generates GNSS orbit products at the 20-millimeter level. However, after the change in the broadcast ephemerides for SVN49 on May 1 we were unable to include this satellite in our routine processing because it not longer passed through our data preprocessing steps. (We will explain this point a little later.) This exclusion of the satellite coupled with the reported signal anomaly triggered the analysis presented here.

To study the SVN49 signal anomaly we use IGS data (available at http://igs.org) from the time period of April 30 to May 30. We begin on April 30 because this is one day before the Air Force changed their handling of SVN49, based on an investigation into the signal anomaly and development of a method for correcting it conducted by the GPS Wing. This gave rise to a significant change in the broadcast ephemerides values for the spacecraft.

For the analysis presented here we used a processing scheme that is very similar to the processing we use for the generation of our highest quality products, i.e., the postprocessed observations we submit to the IGS as contribution to the so-called IGS final products. But we significantly increased the tolerance in our data preprocessing to ensure that the data from SVN49 would not be excluded from our calculations.

The results of our analysis will allow us to compare our orbit and clock estimates for SVN49 to the broadcast information. This should clearly show what is currently being done with the SVN49 broadcast ephemerides. Furthermore, the residuals of our processing should clearly reveal the signal anomalies.

Orbit and Clock Differences

First, let us take a look at the differences between our estimated orbits and clocks and the orbit and clocks as given by the GPS broadcast ephemerides. **Figure 1** shows the radial orbit difference for all the active GPS satellites for days 120 and 121 of 2009 (April 30 and May 1). Only SVN56 was excluded because it had undergone a repositioning maneuver on April 30 during which its transmissions were set unhealthy.

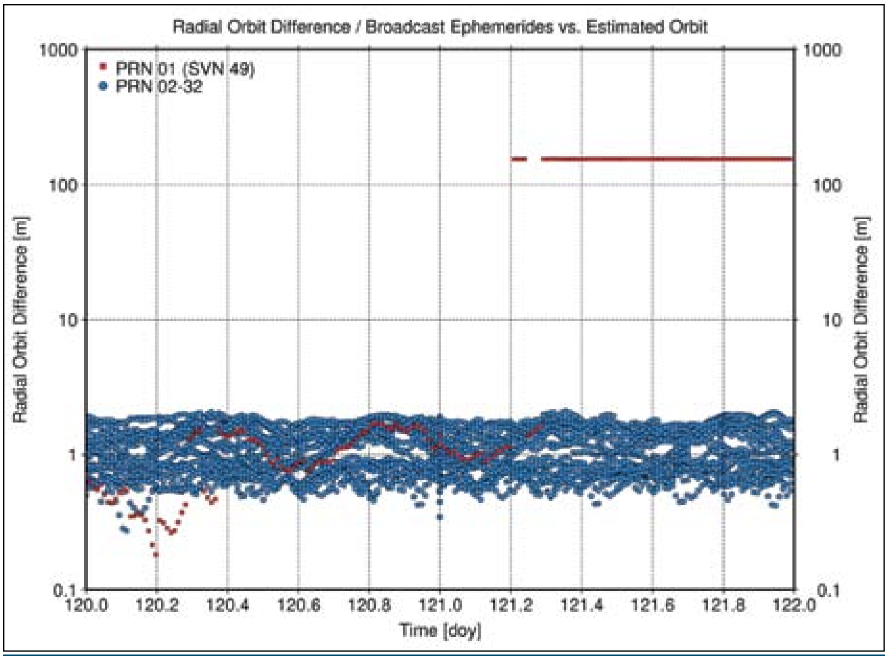

FIGURE 1 Radial orbit differences between GPS SVN49 broadcast ephemerides and estimated orbits

The figure nicely illustrates the dramatic change in the broadcast ephemerides of SVN49 starting on May 1, 2009. After May 1 this difference has remained very constant in time with the radial orbit difference remaining at 150 meters and the clock difference at 500 nanoseconds. Note that the broadcast orbit is 150 meters above the estimated orbit.

Until April 30 the broadcast ephemerides of SVN49 behaved very similarly as those of all other satellites. After April 30 this changed dramatically for no apparent reason. However, the change in orbit and clock is in itself consistent such that an "ordinary" user of the system would actually not notice this effect.

The 150-meter orbit difference is fully reflected in the satellite clock bias. Hence, the user range error is almost unaffected by this change. We notice this 150-meter offset in our software because in our preprocessing we perform an orbit fit through the broadcast ephemerides.

This leads to some problems because the orbit resulting from the fit has to "obey" the equations of motion of the satellite center of mass. The resulting orbit fit therefore has an RMS agreement with the broadcast ephemerides at the 80-meter level, whereas for normal GPS satellites the agreement after fit is at the 1-meter level.

Consequently our resulting a priori orbit is no longer consistent with the a priori clock offsets coming from the broadcast ephemerides. This discrepancy, at the 80-meter level, leads to the exclusion of the satellite in our preprocessing.

SVN49 Signal Anomaly

As the next step, let us look at the reported signal anomaly on SVN49. In the work we do at ESOC the most important observation type is the carrier phase observation. The pseudoranges are used for preprocessing, to determine the absolute value of the receiver and transmitter clock offsets, and for integer ambiguity resolution. This relative unimportance of the pseudorange observations is also reflected in the fact that the weight of the carrier phase observations in our postprocessing algorithms is 1,000 times larger than the weight of the pseudorange observations.

This also means that an anomaly in the carrier phase observations would seriously affect us whereas an anomaly in

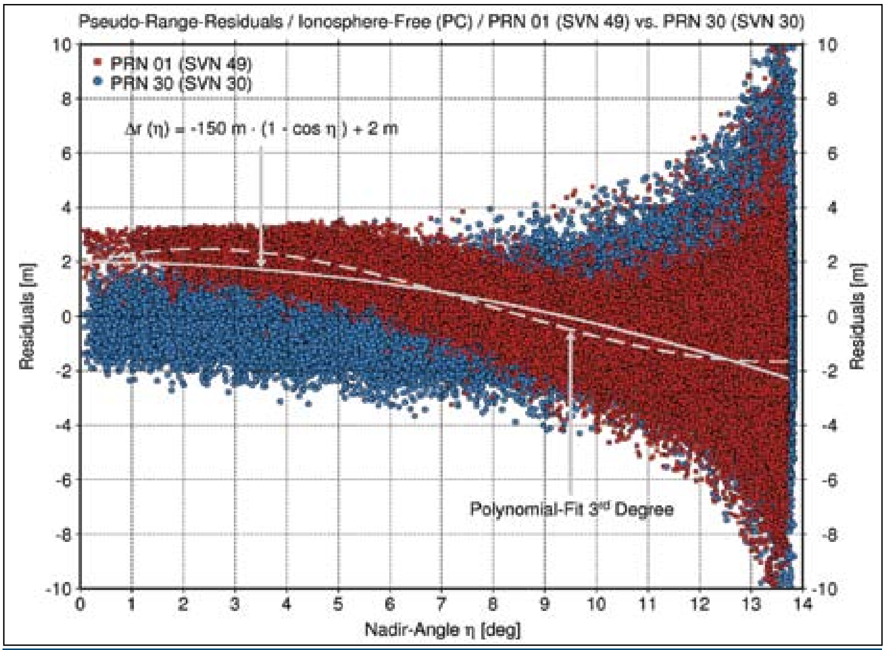

FIGURE 2 Ionosphere-free pseudorange residuals for SVN49 and SVN30

the code observations would have hardly any effect. Furthermore, we should note that as pseudorange and carrier phase observables we use the ionosphere-free linear combination of the observations on the two (L1/L2) frequencies.

Elevation Dependence

Figure 2 shows the pseudorange residuals of all the processed days (31 days) for SVN49 as a function of the nadir-angle η. For those not familiar with the term, "nadir" is the equivalent of the zenith angle.

For observations from the Earth to a satellite, the "zenith angle" is used to indicate the height of satellite with respect to the station's horizon. For observations from a satellite to the Earth, the "nadir angle" is used to indicate the height of a station with respect to the satellite's horizon. For comparison, the residuals for SVN30, which is practically in the same orbital slot as SVN49, are included in the same figure.

The pseudorange residuals for SVN30 are representative of all other GPS satellites. The residuals for SVN49 are clearly different: they show a clear nadir dependence of the pseudorange residuals with a peak-to-peak difference of about four meters.

In our analysis, this indicates that the mean and the RMS of the SVN49 residuals are significantly higher than those of the other GPS satellites. The mean is typically around zero but for SVN49 it reaches approximately -1 meter. For SVN49 the RMS of the residuals reaches a magnitude of two meters whereas for the other GPS satellites it is at the one-meter level. The non-zero mean of the residuals is unpleasant because this could have a serious effect on our integer ambiguity resolution in which the code observations are used.

Although the non-zero mean and the clear elevation-dependent bias are not "state-of-the-art" they do not really pose any serious issue and the satellite could be used in an almost fully normal fashion. If the bias is stable over time, it would even be possible to remove it by applying an elevation-dependent correction, for example, an antenna offset, for the pseudorange observations.

In the figure of the SVN49 residuals we have included a polynomial fit that would remove much of the observed pattern. Applying such a corrective polynomial in our software is a very trivial task.

This in fact brings us back to the 150-meter discrepancy between the SVN49 orbit estimates and the broadcast ephemeris. In principle the observed nadir-dependent pattern can also be absorbed to a large extend by applying a (large) value for the satellite antenna offset, i.e., the distance between the GPS transmitter antenna and the satellite center of mass. A large antenna offset would "automatically" correct the observations according to the following equation:

$$\Delta r(\eta) = \Delta z \cdot (1 - \cos \eta)$$

To illustrate how this works we have introduced the observed orbit bias (Δz = -150 meter) as antenna offset in the foregoing equation and plotted the resulting curve in the SVN49 residual plot. We have shifted the curve by +2 meters to align it to the observed offset for the nadir-angle of 0 degrees. The figure clearly shows that by applying an — of course, artificial — antenna offset of -150 meters most of the SVN49 anomaly can be absorbed.

With this we discovered the explanation of the biases observed in the broadcast ephemerides. The U.S. Air Force is applying an (artificial) antenna offset of -150 meters for SVN49 in order to alleviate the signal anomaly. Our fitted polynomial would of course do a better job, but the artificial antenna offset approach allows the usage of SVN49 by all normal "navigation" users without any software modification on the user side.

We performed some further analysis to determine on which signal the anomaly is most pronounced. There we found that the anomaly comes from the code observations on the L1 frequency and that the effect is equally large on the C/A- and P-code.

Other Satellites

As mentioned at the beginning of this article, we extended our investigation to other Block IIR and IIR-M satellites that ESOC routinely processes and found that several of these also exhibit a similar, though much smaller anomaly.

The most conspicuous residuals are observed for SVN55 and SVN43. **Figure 3** illustrates the anomaly for SVN55.

The figure shows an anomaly for SVN55 at approximately the one-meter level, which is much smaller than the four-meter level of SVN49; however, the nadir-dependent (from the perspective of the satellite) pattern is very similar as the one observed for SVN49. Because of the very small size of the anomaly this effect had not been noticed until now.

The one-meter bias for a nadir angle of zero degrees (i.e., an observation in the zenith of the Earth-fixed observer) is easily overlooked in any statistical analysis, given the strong increase of the noise of the observations with increasing nadir angle. The anomaly of SVN43 looks very similar.

Furthermore, anomalies seem to be present on signals from SVNs 41, 44, 58, 59, 60, and 61. So, of the 19 Block IIR and IIR-M satellites that we analyzed, 9 show an anomaly at the one-meter level in their pseudorange observations.

At the same time none of the 11 Block IIA satellites or the 18 active Russian GLONASS satellites that we analyzed shows any sign of anomalies in the pseudorange observations. We therefore suspect that those Block IIR and IIR-M satellites that show a pseudorange anomaly have some kind of electronic equipment connected to their auxiliary port.

Unresolved Issue

In the scope of these anomaly investigations one additional interesting aspect surfaced. We noticed that the residuals of the IGS station ZIM2 (Zimmerwald, Switzerland) did not show the SVN49 anomaly. After some investigation we found that ZIM2 represented a model of GPS/GLONASS receiver that was tracking unhealthy satellites. Some further "data mining" revealed two other such receivers with data for SVN49, ROSA (Rosana, Brasil) and GANP (Ganovce, Slovakia).

All three receivers behave similarly in that they do not show the SVN49 data anomaly or, at least, show it at a much less pronounced level. This is clearly seen in Figure 4.

The reason for this receiver behavior is unclear at present. One possibility is that this model of receiver is performing some heavy carrier phase smoothing of the pseudorange observations, effectively replacing the pseudorange observations with the carrier phase observations.

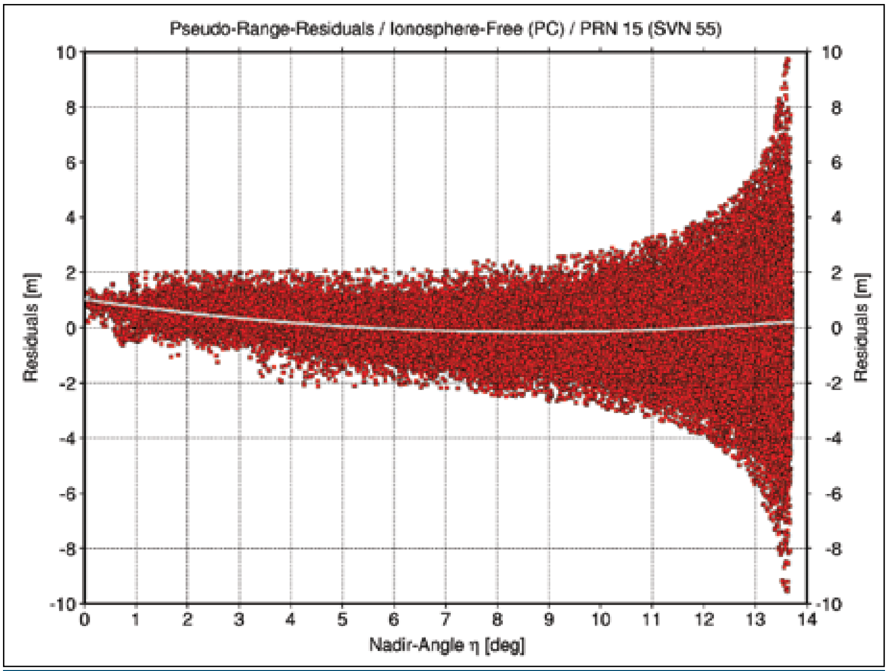

FIGURE 3 Pseudorange residuals on GPS SVN55

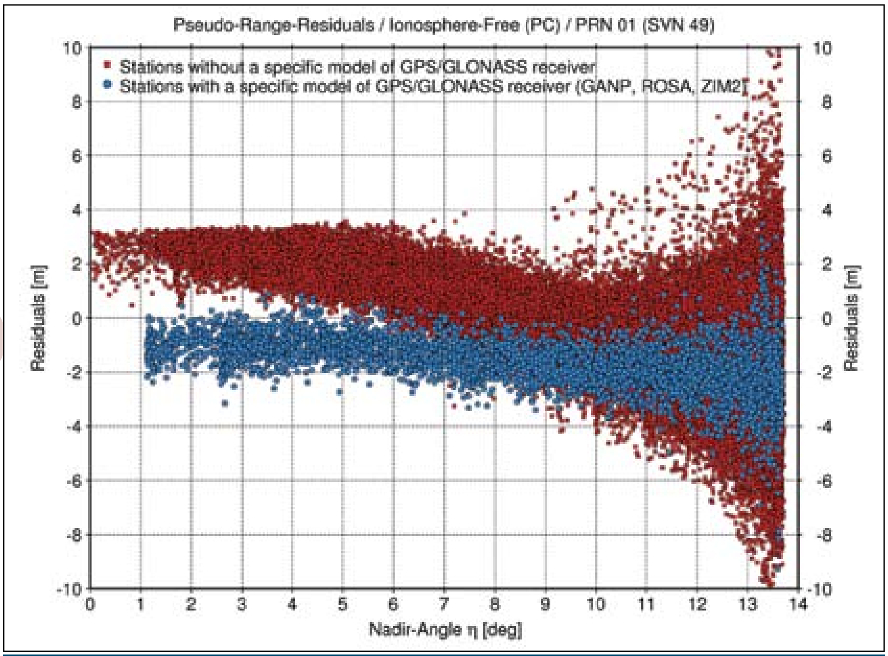

FIGURE 4 Pseudorange residuals for stations equipped with and without a specific type of GPS/GLONASS receiver

However, the noise of the pseudorange residuals contradicts this assumption. So the most likely assumption is that the (pseudorange) tracking loop of this receiver type is significantly different from all other receivers used.

The fact that this results in "anomaly free" observations of SVN49 gives some hope for the future of this satellite and could help in finding and understanding the root cause of the anomaly itself. We also found several examples of a different model of GPS-only receiver from the same manufacturer that were tracking SVN49, and they showed the same behavior as the GPS/GLONASS receivers.

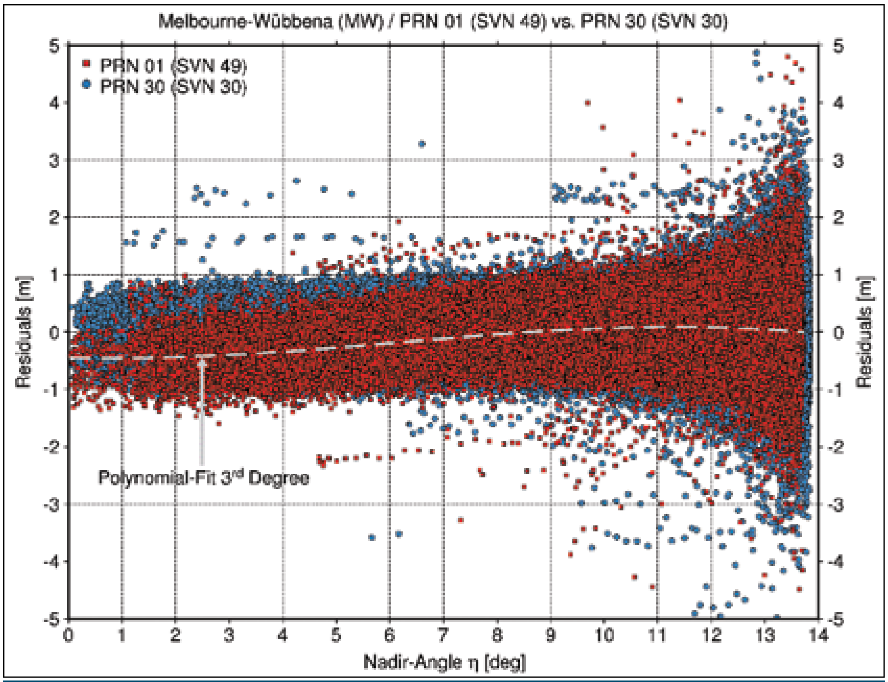

FIGURE 5 Residuals for the Melbourne-Wübbena linear combination

Conclusions

We have clearly shown that a significant issue exists with the code observations of GPS SVN49 (PRN01) whereas the carrier phase observations seem to perform nominally. The issue manifests itself as an elevation-dependent bias with a peak-to-peak difference of approximately four meters in the ionosphere-free observations (PC).

We have furthermore demonstrated that the broadcast ephemerides of this satellite are altered by approximately 150 meters (and 500 nanoseconds for the clock) and have shown that this is done to reduce the effect of the observed anomaly. An artificial shift of the satellite antenna offset by 150 meters does correct a significant amount of the observed elevation-dependent code bias.

The carrier phase observations seem to be fine, as we can do integer ambiguity resolution without too much problems. However, using the code observations for aiding the ambiguity resolution, for example, using the well-known Melbourne-Wübbena (MW) linear combination, is not advisable as is demonstrated **Figure 5**.

The figure illustrates that the effect of the anomaly on the MW observations is at the one-meter level, which means that it is of similar size as the wavelength of the MW linear combination (0.86 m). Therefore, finding the correct integer number of cycles will be difficult.

The different size of the bias in the ionosphere-free observations and the Melbourne-Wübbena observations is because these observations are based on different linear combinations of the dual-frequency observations. The bias is present only, or at least mainly, in the observations of the L1 frequency and thus its "amplification" is different for the PC and the MW linear combinations.

We conclude that with the currently implemented "correction scheme," which uses an artificial satellite antenna offset of -150 meters, most regular "navigation" users of GPS will be able to use the satellite without any loss of accuracy.

However, high-end users, especially those performing ambiguity resolution using code observations, will have to model the anomaly more accurately, e.g., using a third-order polynomial as we have done here. Of course, the model should be derived for the code observations on the L1 frequency to ensure that both the PC and the MW observations are properly corrected.

The GPS Wing is currently gathering information from manufacturers and user communities regarding the effect of the SVN49 anomaly on a wide range of GPS products and applications. The research will be used to reach a decision on whether or not to set the satellite healthy and, if set healthy, what to do to mitigate the signal anomaly prior to setting it healthy.

Acknowledgment

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Manufacturer

The GPS/GLONASS receiver model that was able to track SVN49 without modification, as reflected in Figure 4, is the NetR5 from **Trimble**, Sunnyvale, California. The GPS receiver that also was able to track the anomalous signals was the Trimble NetRS.

Authors

Tim Springer received his M.Sc. from the Faculty of Aerospace Engineering in Delft, The Netherlands and his Ph.D. from the Astronomical Institute of the University of Berne in Switzerland. He has been a key person in the development of the Centre for Orbit Determination in Europe (CODE), the Bernese software, and the IGS orbit and clock combination software. Since 2004 he has led the GNSS developments at the Navigation Support Office of the European Space Operations Centre (ESOC) of the European Space Agency (ESA). In this group he has developed the new ESOC GNSS analysis software, NAPEOS, which has been operational since January 2008. Springer's main GNSS activities at ESOC include the ESA IGS analysis centre, the Galileo Geodetic Reference Service Provider (GRSP), Giove-A and B analysis, and (near) real-time GNSS processing.

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