GPS Jamming and GPS Carrier-Phase Time Transfer

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BIOGRAPHY

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ABSTRACT

This paper studies the impact of GPS jamming on GPS carrier-phase time transfer. To study this issue, at NIST, we have installed a commercial GPS jamming detector since 2014 April. During 2014 April – 2015 April, the detector detected more than 100 jamming events, though there had been a few outages of jamming detection. The jamming events usually last for less than 2 min. We find that almost all jamming events lead to a significant drop in the L1 signal-to-noise ratio (SNR) for all observable GPS satellites. Another thing we notice is that the 3 GPS receivers which are closer to Broadway, a main street in Boulder, Colorado, are more likely to be jammed. This indicates that the jamming source may come from cars passing by. Although a jamming event causes a significant drop in L1 SNR, the GPS receiver can still track the GPS satellites properly for most cases. However, sometimes, the jamming can be too strong and then a GPS receiver may lose track of some GPS satellites. This leads to a GPS-data anomaly. Because of this anomaly, the carrier-phase time transfer processing re-estimates the phase ambiguities at the anomaly. Thus, there is often a time discontinuity at the anomaly. The discontinuity ranges from a few hundred picoseconds to a few nanoseconds. Then the next question is what we shall do when a jamming event occurs? Our earlier study [1] shows that the 9th-order polynomial curve fitting for the code and phase measurements can repair a short-term data anomaly (< 40 min). We apply this technique to repair the anomaly at jamming and it works well. Thus, we can eliminate the impact of a short-term jamming (< 40 min) on carrier-phase time transfer by repairing the GPS data.

I. INTRODUCTION

Global Positioning System (GPS) has been used for time transfer and time synchronization since 1980 [2]. The initial GPS time transfer was based on the GPS code signal. The GPS code time transfer usually provides a 2 – 20 ns accuracy and precision [2-4]. In 1998, people invented the GPS carrier-phase time transfer technique which used the GPS carrier wave to do time transfer [5]. It showed much better short-term stability (< 100 ps) than the GPS code time transfer, because the carrier wave frequency is much higher than the GPS code chipping rate. Since then, the GPS carrier-phase time transfer has drawn a lot of attention [6-11]. After many years of development, it is now a widely-accepted method for high-precision time transfer.

However, there are still some issues in GPS carrier-phase time transfer that have never been studied. For example, although the impact of GPS jamming on positioning has been discussed for many years, the impact of jamming on timing has drawn little attention. Especially, we do not know of any paper discussing the impact of jamming on GPS carrier-phase time transfer. This paper focuses on the relation between GPS jamming and GPS carrier-phase time transfer.

Section II discusses the impact of GPS jamming on GPS carrier-phase time transfer. Section III proposes a post-processing method to eliminate the impact of GPS jamming on GPS carrier-phase time transfer. Section IV gives the summary.

II. IMPACT OF JAMMING ON GPS CARRIER-PHASE TIME TRANSFER

To study the impact of GPS jamming on GPS carrier-phase time transfer, we have installed a commercial GPS jamming detector at NIST since 2014 April. The physical architecture of the jamming-detecting system is quite simple. Essentially, a GPS antenna was installed on the roof of the NIST building. The location of the antenna is close to Broadway, a main street in Boulder, Colorado. The antenna receives the GPS signal and sends the signal to a splitter via a cable. The two output ports of the splitter are connected to the two input ports of the jamming detector, respectively. The jamming detector determines if a jamming event occurs or not, using two methods which will be discussed in the next paragraph. The result is saved in a computer.

Here is a description of how the jamming detector works. The jamming detector uses two methods to detect a jamming event at the L1 frequency. Each input port of the jamming detector uses each method. The decision based on the combination of both methods can improve the confidence of jamming detection. The first method is "spectral power detection." The jamming detector measures power in the L1 GPS band. The system initially measures the average power in the band and sets a mask a little above that. Then when it detects power greater than that mask, it starts saving the measurements and flags the beginning of a jamming event. It continues until the power drops below the mask again. The second method is "signal-to-noise-ratio (SNR) detection." The jamming detector measures the L1 SNR on each satellite each day for each pass, estimating multipath events. Using these data, the system sets a mask for minimum SNR for each satellite as a function of time in each pass. When the SNR drops below the mask, the system flags a potential jamming event on that satellite and stores the SNR. It continues until the SNR resumes above the mask.

The jamming detector almost continued running from April 02, 2014 to April 26, 2015, although there have been a few outages of jamming detection. During the whole time period, the detector detects 146 jamming events. Figure 1 shows the statistics of the jamming event duration. A jamming event usually lasts for less than 2 min.

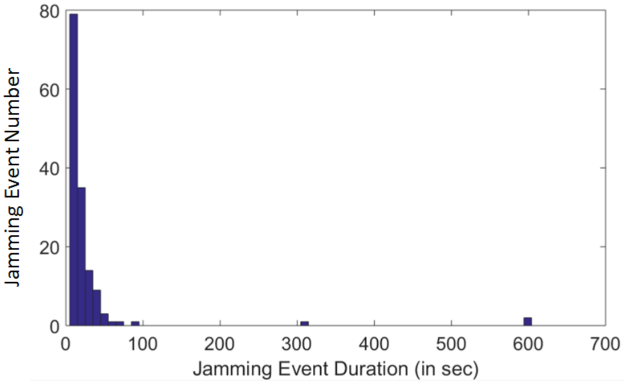
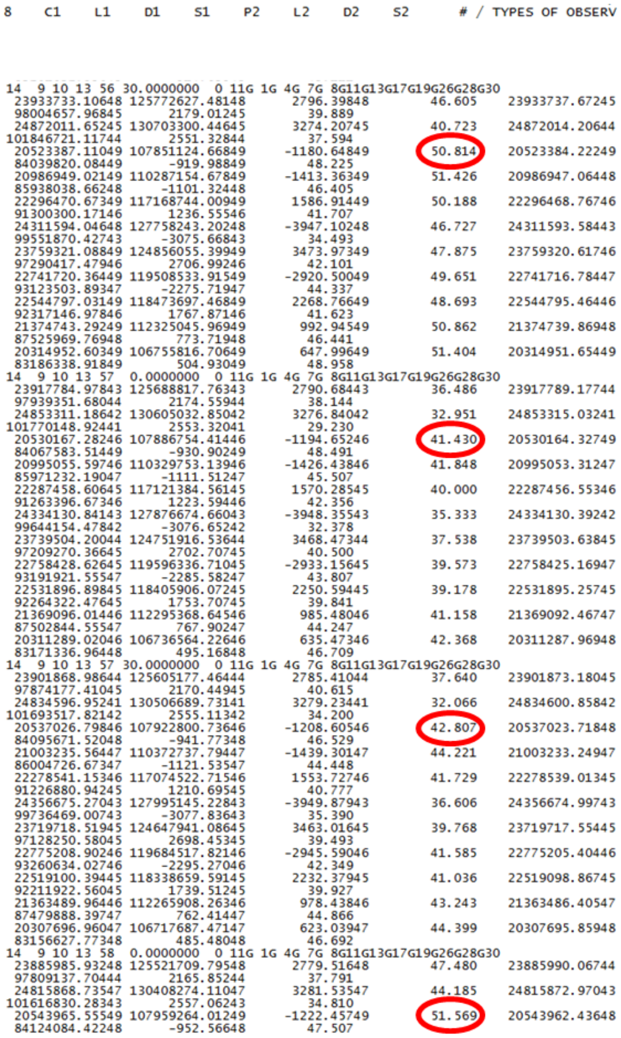


Figure 1. Statistics of jamming event duration.

At NIST, we had 7 GPS receivers running properly for most time of 2014. Three of them have antennas close to the Broadway. They are *NISY*, *NISX*, and *NIS2*. Note, *NISX* stopped working during Aug. 27, 2014 – Sep. 23, 2014. The rest four of them have antennas far away from Broadway. They are *NIST*, *NISW*, *NISS*, and *NISA*. We find that when a jamming event occurs, there is usually an obvious drop in the L1 SNR of all observable GPS satellites, for those GPS receivers whose antennas are close to Broadway. The L2 SNR sometimes has a drop, and sometimes not. This depends on whether the jamming aims at L1 only or at both L1 and L2. On the other hand, for those GPS receivers whose antennas are far away from Broadway, the SNR at both L1 and L2 is not affected at a jamming event. This indicates that the jamming source may come from cars driving on Broadway. As an example, the jamming detector detected a jamming event at ~13:56:30 on Sep. 10, 2014. The jamming event last for 54 s. As a result, we see a significant drop in the L1 SNR of all observable GPS satellites at 13:57:00 and 13:57:30, for the *NISY* receiver (Figure 2). The red ovals in Figure 2 illustrate the L1 SNR drop of PRN07 during the jamming event. From Figure 2, we can also see that there was no significant drop for L2 SNR. We find the same thing for the *NIS2* receiver, whose antenna is also close to Broadway. We should mention that the *NIS2* receiver can receive both GPS signals and Glonass signals. And there was no change or negligible change in the SNR of Glonass signals, during this jamming event. This indicates that this jamming event aimed at GPS L1 signal only. On the other hand, for those receivers whose antennas are far away from Broadway, we do not find any obvious change of SNR at L1 and L2. Thus, we know that this jamming event is very likely to come from a car driving on Broadway.



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  85938038.66248     -1101.32448          46.405
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  21003235.56447 110372737.79447     -1439.30147        44.221    21003233.24947
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  22278541.15346 117074522.71546      1553.72746        41.729    22278539.01345
  91226880.94245      1210.69545          40.777
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  97128250.58045      2698.45345          39.493
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  93260634.02746     -2295.27046          42.349
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  84124084.42248      -952.56648          47.507
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Figure 2. RINEX (i.e., Receiver Independent Exchange Format) data recorded by the *NISY* receiver, on Sep. 10, 2014.

Another thing we find is that most time, a GPS receiver can still track the GPS satellites properly at jamming, although its SNR is dropped as mentioned earlier. In other words, the code and phase measurements are not affected by a jamming event, for most cases. As an example, a jamming event was detected during 16:37:00 – 16:47:00 on Modified Julian Date (MJD) 56839 (i.e. Jul. 01, 2014). Similar to the above example, we again notice a significant drop in the L1 SNR. The *NISY* phase-measurement data for PRN03 during 16:20:00 – 16:55:00 is shown by Figure 3(a). Then we do a high-order (here, 6th-order) polynomial fitting for Figure 3(a) and get the residual shown by Figure 3(b). The two black dotted lines in Figure 3(b) mark the time interval of the jamming event. We can see that there is no outlier/step between the two black dotted lines. This indicates that there is no error in the PRN03 L1 phase measurement when the jamming event occurs. Similarly, we check all observable GPS satellites and all types of measurements (L1, L2, C1, P2) and there is no obvious error in the GPS data at this jamming event. This indicates that this jamming event does not lead to an error in code/phase measurements. Next, we do the GPS carrier-phase time transfer between UTC(NIST) and International GNSS Service (IGS) time scale, using the GPS data on MJD 56839. In this way, we can tell if this jamming event does have an impact on carrier-phase time transfer or not. The result is shown by Figure 4. We can see that for all GPS receivers at NIST, there is no time-transfer error at ~ 16:37:00 on MJD 56839.

Following the above procedures, we find that for most jamming events, there is neither an error in the GPS data, nor an error in the GPS carrier-phase time transfer result. This indicates that most jamming events have no impact on GPS carrier-phase time transfer.

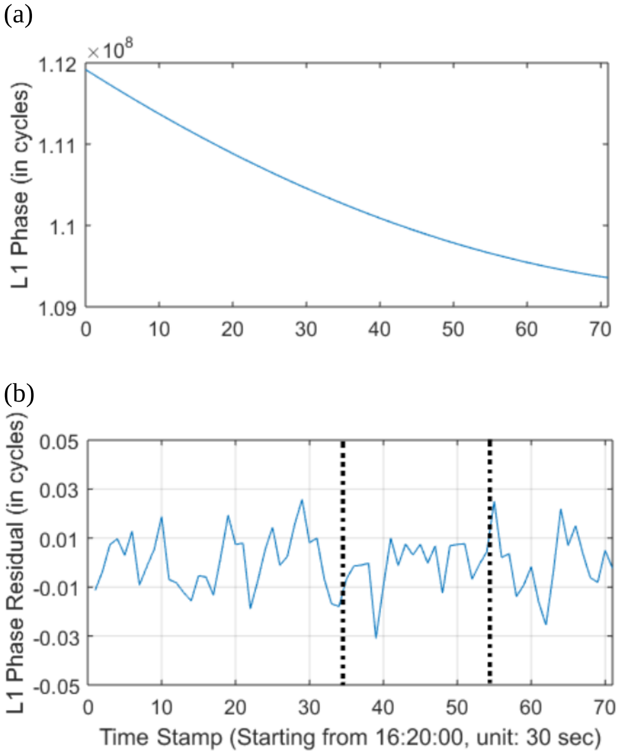

Figure 3. *NISY*'s PRN03 L1 phase-measurement data (a) and its residual (b), during 16:20:00 – 16:55:00. Note, we have applied the satellite-clock-bias correction for the phase-measurement data in (a) to remove the satellite clock noise. The jamming event spans between the two black dotted lines in (b).

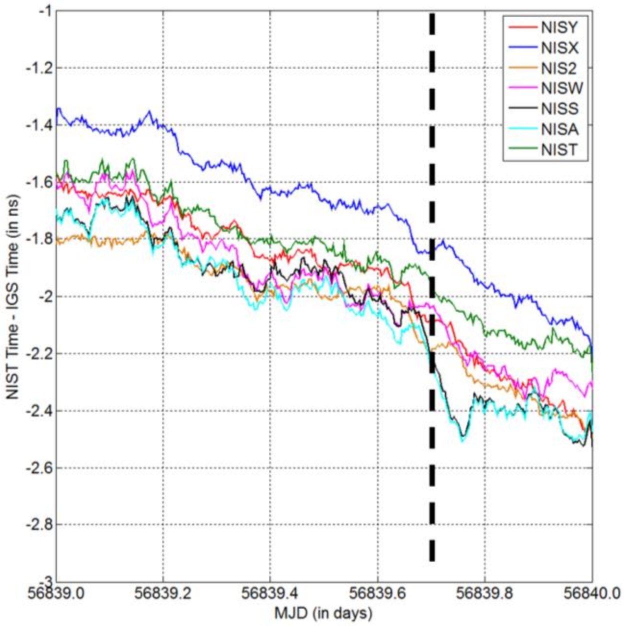

Figure 4. GPS carrier-phase time transfer results on MJD 56839 (i.e., Jul. 01, 2014). A jamming event occurs at approximately 56839.692, which is marked by the black dashed line. This event does not lead to a carrier-phase time-transfer error. Note, the curves are shifted for a better comparison.

However, the above conclusion is not true for all jamming events. In fact, we find 4 jamming events during the whole year which lead to time-transfer errors for some GPS receivers. The 4 events were on Nov. 15, 2014, Jan. 23, 2015, Jan. 26, 2015, and Apr. 21, 2015. Here, we study the case of Jan. 26, 2015, as an example. The jamming detector found a jamming event at ~15:18:30. It last for 43 s. Because of this, *NISY* only observed 1 GPS satellite at 15:18:30 (MJD 57048.638), *NISX* observed 0 satellite, and *NIS2* observed 2 satellites. Notice, these three receivers' antennas are close to Broadway. Other receivers (*NISW*, *NISS*, *NISA*, and *NIST*), whose antennas are far away from Broadway, observed 9 GPS satellites. The carrier-phase time transfer results of all receivers are shown by Figure 5. Clearly, *NIS2* has a jump of greater than 5 ns! We can also see that the slope of *NIS2* is not obviously affected. As for *NISY* and *NISX*, there is no obvious jump at jamming. The reason why there can be a jump at jamming is that the carrier-phase time transfer processing re-starts at an anomaly, such as jamming, and re-estimates the phase ambiguities. Since the phase ambiguities after the anomaly are usually different from those before the anomaly, we have a jump at jamming. The jump depends on the code noise and it is a rather random number. It can be small (< 100 ps, such as *NISY* and *NISX*), or medium (100 ps – 500 ps), or large (> 500 ps, such as *NIS2*).

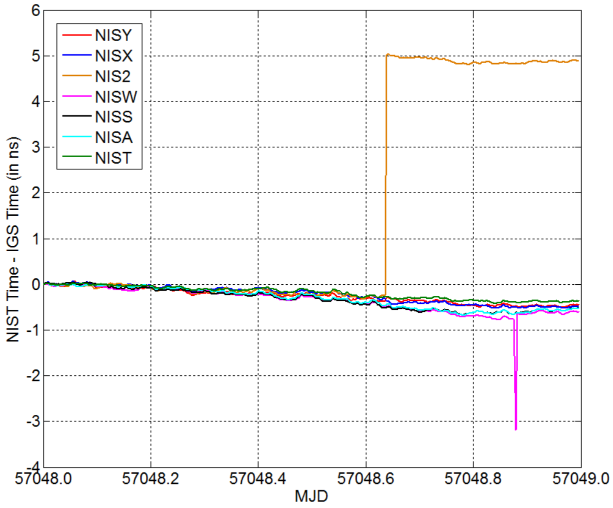

Figure 5. GPS carrier-phase time transfer results on MJD 57048 (i.e., Jan. 26, 2015). A jamming event occurs at approximately 57048.638. This event leads to a carrier-phase time-transfer error in *NIS2*. Note, the curves are shifted for a better comparison.

As another example, on Nov. 15, 2014 (i.e., MJD 56976), there was a jamming event at ~00:13:30. Because of this, *NISY* lost track of 3 GPS satellites, *NISX* also lost track of 3 satellites, and *NIS2* lost track of 1 satellites. The carrier-phase time transfer results are shown by Figure 6. We can see that *NISY* has a jump of about 1 ns at jamming. From the above two examples, we know that a jamming event can sometimes make the observed GPS satellite number fewer than what it should be. This may lead to a jump in carrier-phase time transfer at jamming. Also, we should mention that a jamming event typically does not affect the slope of the carrier-phase time transfer.

To summarize the section, most jamming events do not affect the carrier-phase time transfer. However, when the jamming is so strong that we lose track of some GPS satellites, a timing jump in the carrier-phase time transfer can happen.

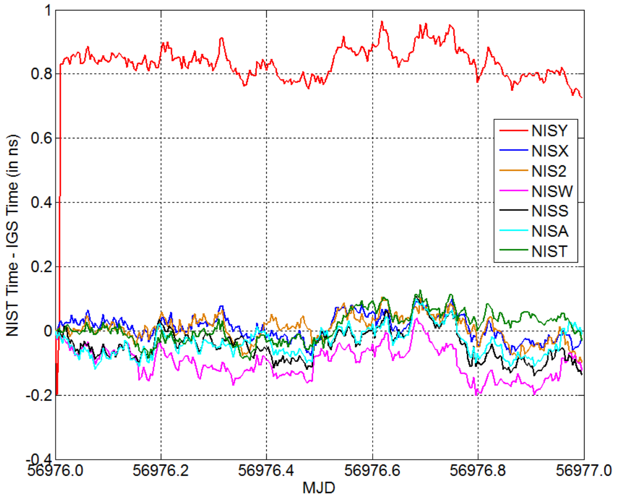

Figure 6. GPS carrier-phase time transfer results on MJD 56976 (i.e., Nov. 15, 2014). A jamming event occurs at approximately 56976.009. This event leads to a carrier-phase time-transfer error in *NISY*. Note, the curves are shifted for a better comparison.

III. ELIMINATING THE IMPACT OF JAMMING ON GPS CARRIER-PHASE TIME TRANSFER

Now we know that a jamming event can lead to the scenario of missing data, and thus invalidate the GPS carrier-phase time transfer result. The next question is that what we shall do when a jamming event occurs.

In 2015, we proposed a GPS-data-repairing technique which can eliminate the time discontinuity at a GPS data error [1]. In that paper, extensive examples were given to verify the technique. Here, we apply this post-processing technique to repair the GPS data at jamming. As an example, we repair the *NIS2*'s GPS data at ~15:18:30 on Jan. 26, 2015 (MJD 57048). The GPS carrier-phase time-transfer result using the repaired data is shown by the red curve in Figure 7. The black curve in Figure 7, which is the same as the black curve in Figure 5 except a constant shift, shows the time-transfer result using the original *NIS2* data. Comparing the red curve with the black curve, we find that the large jump of around 5 ns in the black curve disappears. This indicates that we successfully remove the discontinuity at jamming by the GPS-data-repairing technique.

However, people may wonder if the red curve represents the truth? Is the slope in the red curve correct? To answer these questions, we give the carrier-phase time-transfer result of another NIST GPS receiver, *NISA*. *NISA* has the same reference time as *NIS2*. Thus, the time-transfer result using *NISA* should be the same as that using *NIS2*. As we mentioned earlier, this receiver is far away from Broadway and thus was not affected by the jamming event on MJD 57048. Because of this, the time-transfer result using *NISA* (green curve in Figure 7) represents the true value, and it can be used to verify the correctness of the red curve. Comparing the red curve with the green curve, we can see that the red curve does have the same trend as the green curve. This indicates that the carrier-phase result using the GPS-data-repairing technique is close to the true value.

The above example demonstrates that the impact of GPS jamming on carrier-phase time transfer can be eliminated by the post-processing GPS-data-repairing technique. Admittedly, if the jamming lasts for longer than 40 min, the GPS-data-repairing technique does not work well, as already mention in [1]. However, this long-term jamming event is rare. If it does occur, that is the time we have to find out the jamming source.

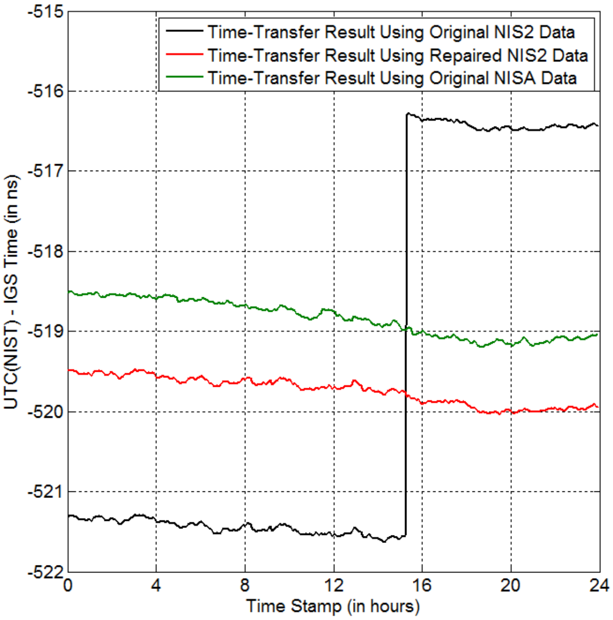

Figure 7. Eliminating the impact of jamming on GPS carrier-phase time transfer. The jamming event occurs at around 15:18:00 on MJD 57048. Note, the curves are shifted for a better comparison.

IV. CONCLUSIONS

To summarize, we have observed more than 100 jamming events during 2014 April – 2015 April. Almost all jamming events lead to a significant drop in L1 SNR for all GPS satellites. However, the significant drop in SNR does not often cause a GPS-data anomaly. Thus, for most cases, the impact of jamming on GPS carrier-phase time transfer is negligible. Nevertheless, sometimes, the jamming can be too strong and we may lose track of some GPS satellites. For these scenarios, the GPS carrier-phase time transfer can possibly have a discontinuity of 100 ps – 5 ns. Statistically, NIST has had 4 strong jamming events which led to time-transfer errors, during a whole year. In this paper, we also demonstrate that the GPS-data-repairing technique successfully eliminates the impact of jamming (< 40 min) on carrier-phase time transfer. This can improve the robustness of carrier-phase time transfer.

ACKNOWLEDGMENTS

The NRCan PPP software is used to realize the GPS carrier-phase time transfer in this paper. The authors thank Francois Lahaye for sharing this software. Chronos Technology Ltd is thanked for providing the GPS jamming detector. We also thank those people who maintain the GPS receivers at NIST. IGS is gratefully acknowledged for providing GPS tracking data, station coordinates, and satellite ephemerides.

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