# A Demonstration of Differenced Dual-Station One-Way Doppler Conducted with Pioneer 11

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*In early 1976 simultaneous one-way doppler demonstrations were performed on Pioneer 11. The data noise of the differenced one-way doppler as computed from the pseudo residuals is around 0.002 Hz, which is nearly an order of magnitude smaller than the one-way doppler noise and about the same as differenced two-way/three-way doppler noise.*

*This report describes the demonstration results and discusses the applicability of differenced one-way radio metric data to spacecraft navigation.*

## I. Introduction

Differenced doppler derived from simultaneous 2-way and 3-way doppler observed at two DSN Deep Space Stations (DSS) is an effective data type for spacecraft navigation. Its advantages over single station doppler is its insensitivity to unmodeled spacecrafts accelerations and its cancelation of the solar plasma. It does suffer, however, from a restricted view period and the loss of geocentric range rate information. Rourke and Ondrasik (Ref. 1) described the information content of differenced doppler. It was shown that the information content in determining geocentric right ascension and declination is equivalent to single station tracking if the equatorial projection of the baseline vector between the two stations is comparable to the distance from the spin axis of a single station. The limitation of common view period (about 4 to 5 h) degrades the information content by approximately a factor of four when compared to full-pass single-station doppler of equivalent data quality. However, if significant unmodeled spacecraft accelerations or space plasma effects exist, the differenced doppler may yield an order of magnitude improvement in navigation accuracy over conventional two-way doppler (Ref. 2).

Normally, differenced doppler is obtained while spacecraft is in 2-way lock with one station, with an additional station in receive-only mode. This is referred to as 2-way/3-way differenced doppler. However, when the spacecraft receiver is out of lock, the doppler signal derived from an on-board oscillator, called one-way doppler, is available at all DSSs in view. Differenced one-way doppler is equivalent to 2-way/3-way doppler and is the subject of this report.

One-way doppler alone has both advantages and disadvantages. On the positive side, one-way doppler passes through the transmission media only once, thus it is affected less than two-way doppler. In addition, for small Sun-Earth-probe angles, the one-way S-X dual-frequency doppler will not have the uplink scintillation problem; thus it is effective in removing the charged particle effects. However, the major difficulty associated with one-way doppler data is the noise from a relatively unstable reference frequency generated from an oscillator on-board the spacecraft. The induced data noise would seriously degrade the data quality for navigation purposes. The ultra-stable oscillator (USO) on the Voyager spacecraft should improve the one-way data quality by at least one order of magnitude compared with earlier on-board oscillators. However, it is not expected that the USO will provide one-way doppler of the same quality as the current 2-way doppler. An easy way to remove the oscillator noise is to difference the one-way doppler simultaneously received at two stations.

The purpose of this study is to demonstrate the concept of removing the oscillator noise by differencing simultaneously received one-way doppler data. If the one-way doppler is simultaneously received at two stations, the noise due to the on-board oscillator is common and, therefore, should cancel after differencing. For two widely separated stations, the differenced one-way doppler should have the same information content as the differenced two-way/three-way doppler. The demonstration was performed in two stages. We first demonstrated the quality of this new data type for performing short baseline and long baseline simultaneous tracking. Two passes of simultaneous short baseline one-way doppler were received at DSSs 42 and 43 from Pioneer 11, and two passes of long baseline one-way doppler were received at DSS 12 and DSS 61/62 from the same spacecraft. Secondly we compared the data quality of differenced one-way doppler with that of differenced 2-way and 3-way doppler. Three passes of simultaneous one-way doppler were obtained with 2-way and 3-way tracking at the beginning and end of each pass. After differencing one can easily compare the data quality of the two types of differenced doppler.

## II. Results and Discussion

In February 1976, two passes (60 min each) of one-way doppler were simultaneously received at DSSs 42 and 43. Later in March, 1976, two passes of 1-hour one-way doppler were received at the California and Spanish stations (DSS 12/DSS 62 and DSS 12/DSS 61). The received data are at S-band with a 60-s count time.

### A. One-Way Doppler

Before we difference the data, let us first examine the quality of the one-way doppler. Pseudo-residuals are shown in Figs. 1 and 2. The average data noise of one-way doppler is around 0.015 Hz, which is about three times noisier than the two-way data taken shortly after the two passes. The increase in data noise is apparently due to the noise from the on-board oscillator. The long bulge in the residuals is believed to be the warm-up drift of the oscillator. The change in residual size of 0.5 Hz over an hour interval suggests that the stability of the oscillator on-board Pioneer 11 is no better than $\Delta f/f = 2 \times 10^{-10}$. Voyager is equipped with an ultra-stable oscillator (USO) and the stability is an order of magnitude better[1]. Whether the one-way data USO is useful for high precision navigation will depend on the ability to calibrate at linear drifts to within a few parts in $10^{12}$. In that case, simple one-way doppler would warrant a closer look.

### B. Differenced One-Way Doppler

Once the short baseline simultaneous data were differenced, nearly all the noise due to the oscillator cancels. The bias in the differenced one-way doppler residuals is down to the insignificant level of mHz or less with data noise less than 2 mHz ($1\sigma$) (Fig. 3). This shows about the same data quality as the two passes of two-way/three-way doppler taken at the same two stations two years earlier (Ref. 3). The two stations share a common frequency standard, thus no bias due to frequency offset is expected in the residuals.

The results of the two long baseline passes are not much different from that of the short baseline data in data noise which is around 2 mHz. There are biases as large as 12 mHz with slopes of 2 and 4 mHz per hour (Table 1). These biases are believed to be due to the relative frequency offset between the two stations. The slopes of 2 to 4 mHz/hr are too large to be due to the drift between the two frequency standards (Ref. 3). These slopes are probably due to the ionospheric effect together with the orbit error of Pioneer 11. The local time was 1 to 2 P.M. at DSS 12 and 9 to 10 P.M. at DSS 61/62. The estimated effect due to ionosphere is in the range of 2 to 4 mHz/h. We have reasonable confidence that neither the biases nor the slopes are due to the on-board oscillator. Some two-way/three-way doppler data at the beginning and end of each one-way/one-way pass would determine if the bias and slope are due to the on-board oscillator or other causes.

[1] According to the MJS 77 Functional Requirements Book, MJS77-4-2002, the USO will drift about $5 \times 10^{-11}$ per 24 h. However, the linear drift can be calibrated to within $4 \times 10^{-12}$ for an integration time of 1 s over a sample period of 600 s.

In May of 1976 three 2-h passes of simultaneous doppler were received at DSSs 12 and 62. Each pass consisted of three consecutive segments. The first and third segments were 1/2 h of 2-way/3-way tracking. The second segment was an hour of two-way station one-way tracking. This arrangement was intended to give a direct comparison between the two data types. The spacecraft Pioneer 11 was in 2-way lock at DSS 62 and concurrently assumed 3-way tracking at DSS 12. About a half hour later tracking switched to one-way mode at both stations. After one hour of one-way tracking, it returned to the 2-way/3-way mode for another half hour.

Figures 4 to 6 show the pre-fit residuals of one-way, 2-way and 3-way doppler data, with the differenced 2-way/3-way and one-way (DSS 62) doppler. Even though the one-way drifted tens of Hz due to the warm up of the spacecraft oscillator and was quite noisy (~0.1 Hz), differenced doppler based on one-way data was just as good as differenced doppler based on 2-way/3-way data. The two data types show no relative bias and no inherently different noise (Table 2) characteristics when space plasma is at low levels. Therefore, the navigation performance based upon differenced doppler data is the same if either 2-way/3-way data or 1-way/1-way data is used. The constant bias in both the 2-way/3-way and 1-way/1-way residuals is due to the frequency offset between the two station clocks. This suggests that differenced one-way doppler may be used as a tool to determine frequency offset in the same manner as differenced 2-way and 3-way doppler.

## III. Conclusion

The encouraging results of these demonstrations strongly indicate that the differenced one-way doppler is equally good in data quality as the 2-way/3-way differenced doppler. Thus the differenced one-way doppler becomes a new data type for navigation without any hardware changes. This data type is effective in removing unmodeled spacecraft accelerations and space plasma effects. Future missions such as Pioneer/Venus and Galileo will be using one-way doppler for navigating the probe before impact to the planet. About 20 min of one-way doppler will be used to pinpoint the impact location on Venus during the critical period of Pioneer/Venus probe mission.

The recent receiver failure on the Voyager 2 spacecraft may require the navigation team to use differenced one-way doppler which can provide differenced doppler of the same quality as specified by Voyager mission requirements for 2-way/3-way data.

# Acknowledgement

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# References

1. Rourke, K. H., and Ondrasik, V. J., "Application of Differenced Tracking Data Types to the Zero Declination and Process Noise Problems," in Technical Report 32-1526, Vol. IV, *The Deep Space Network Progress Report* Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1971.

2. Chao, C. C., and Ondrasik, V. J., "The QVLBI Doppler Demonstration Conducted with Mariner 10," JPL *Deep Space Network Progress Report, 42-47,* Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1975.

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**Table 1. Summary of statistics of differenced one-way doppler (60-s count time)**

| DSS difference, (date) | Bias, $H_z$ | Slope, $H_z/h$ | Noise, $(1\sigma)$, $H_z$ |
|---|---|---|---|
| 42–43 (2/8/76) | 0.0011 | 0.0 | 0.0014 |
| 42–43 (2/19/76) | 0.00057 | 0.0 | 0.0020 |
| 62–12 (3/17/76) | 0.0126 | 0.0043 | 0.0018 |
| 61–12 (3/17/76) | 0.0011 | 0.0027 | 0.0025 |

**Table 2. Summary of differenced doppler data noise**

| Pass and date | $\sigma_{2\text{ way} - 3\text{ way}}$ (start of pass), Hz | $\sigma_{1\text{ way} - 1\text{ way}}$, Hz | $\sigma_{2\text{ way} - 3\text{ way}}$ (end of pass), Hz |
|---|---|---|---|
| First pass, May 15 | 0.00385 | 0.00307 | 0.00265 |
| Second pass, May 18 | 0.00402 | 0.00310 | 0.00295 |
| Third pass, May 24 | 0.00367 | 0.00249 | 0.00301 |

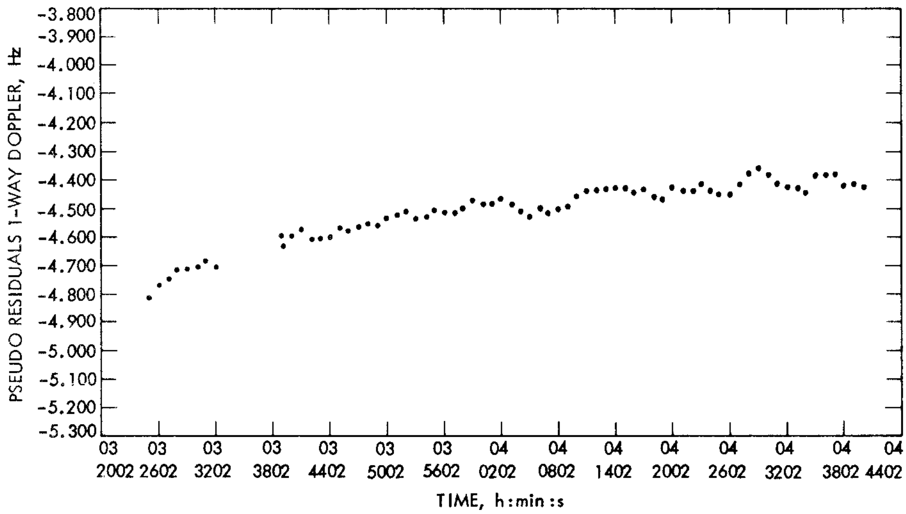


**Fig. 1. Pseudo residuals of one-way doppler at DSS 42, Feb. 8, 1976**

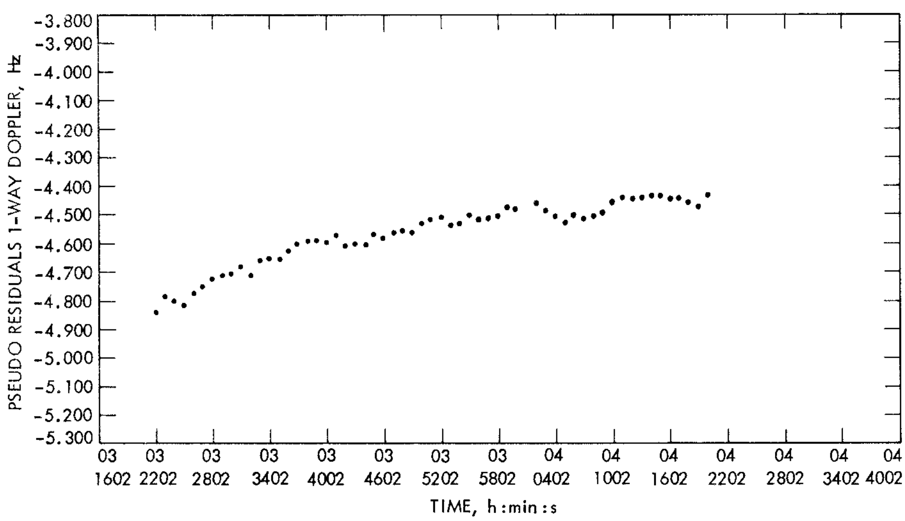


**Fig. 2. Pseudo residuals of one-way doppler at DSS 43, Feb. 8, 1976**

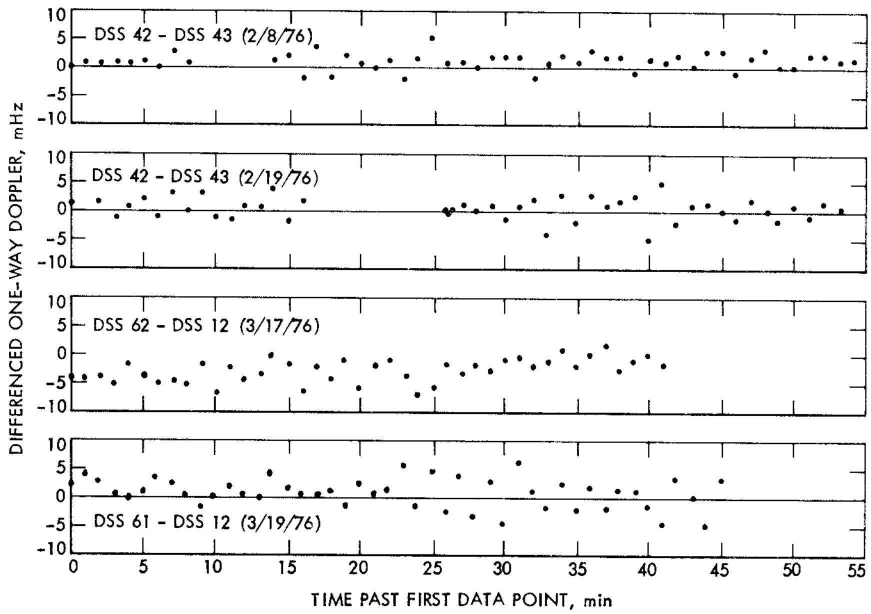


**Fig. 3. Pseudo residuals of differenced two-station one-way doppler from Pioneer 11**

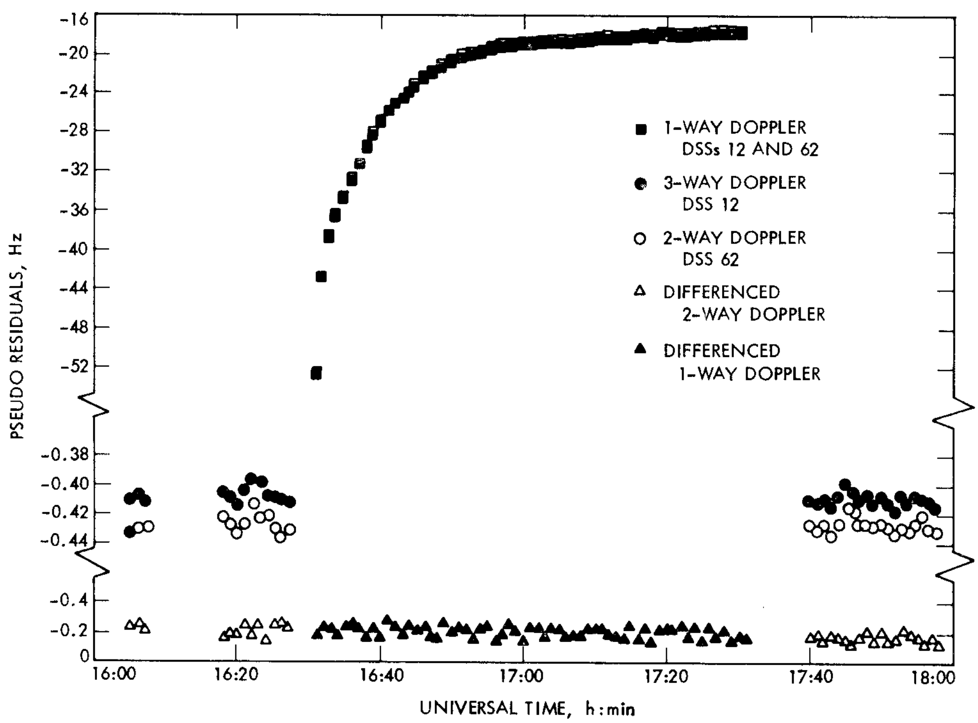


**Fig. 4. Pseudo residuals of simultaneous and differenced doppler from Pioneer 11**

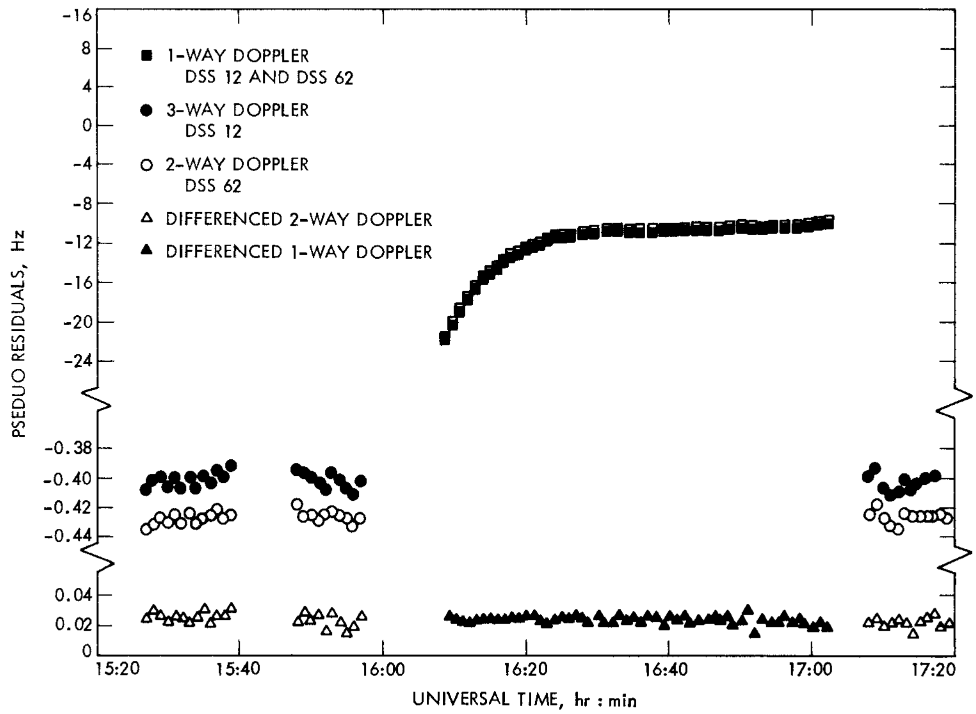


Fig. 5. Pseudo residuals of simultaneous and differenced doppler from Pioneer 11, May 18, 1976

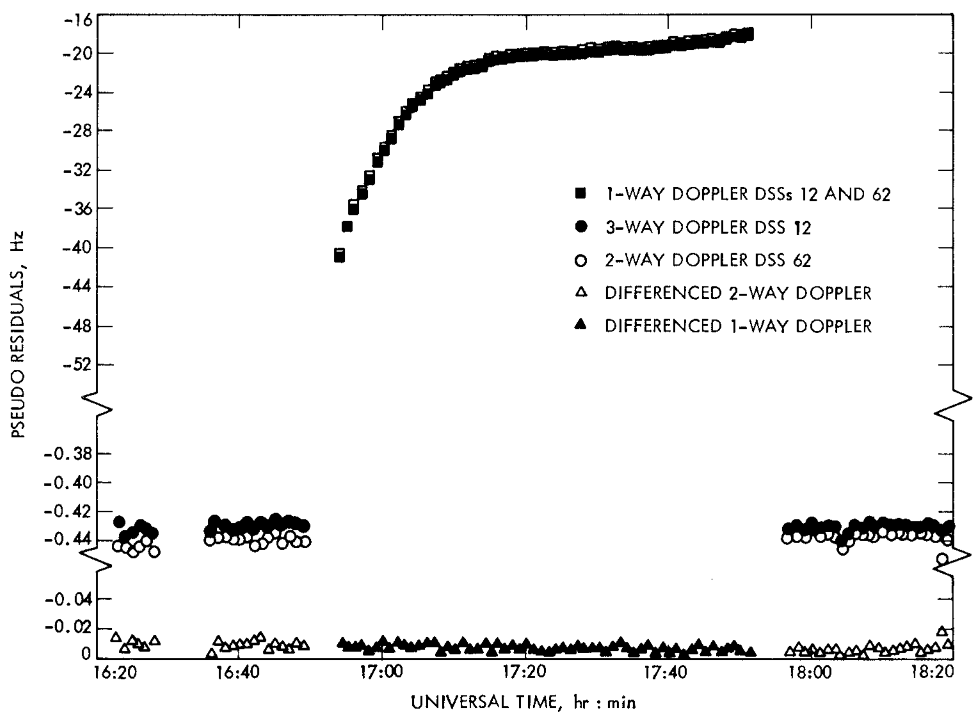


Fig. 6. Pseudo residuals of simultaneous and differenced doppler from Pioneer 11, May 15, 1976