Pseudo-DRVID: A New Technique for Near-Real-Time Validation of Ranging System Data

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Near-real-time validation of doppler and angular radio metric data has been quite successful and an established fact for the last decade. Near-real-time validation of ranging system data, however, has for the most part been ineffective. Reasons are here presented as to why the doppler and angle validation techniques cannot successfully be applied to ranging system data. A new technique is described which can validate sequential range acquisitions in near-real-time to the 10-meter level.

I. Introduction

Near-real-time validation of doppler frequency data (the primary orbit determination data type) has been generally performed since 1965 and has proved to be enormously successful in identifying problem areas within the Deep Space Network (DSN) tracking system in a convenient and timely fashion. On the other hand, near-real-time validation of ranging system data (the secondary, but very important, orbit determination data type), although an oft-iterated and earnestly sought after goal, has in general proved both elusive and unsatisfactory. In particular, near-real-time validation of ranging system data from the current prime ranging system, the Planetary Ranging Assembly (PRA), has (until recently) been superficial and unevenly performed. The reasons why the current near-real-time radio metric data validation techniques, which have proved so successful with doppler data, fail when applied to ranging system data become apparent when the differences in the nature of doppler data acquisition vs ranging system data acquisition are considered. The crux of these differences is that the doppler system makes frequent measurements which are independent in and of themselves, while the PRA makes infrequent measurements of a quantity (not identically range!) which will, when combined with very precise orbital foreknowledge, produce a range measurement. In the following sections, the difficulties with and the inappropriateness of applying the current near-real-time radio metric data validation techniques to ranging system data will be explored. Finally, a new and far more satisfactory technique, referred to as "Pseudo-

DRVID"[1] will be presented, in combination with some preliminary, but illustrative results of the new technique.

II. Description of Current Near-Real-Time Radio Metric Data Validation Techniques

The current near-real-time radio metric data validation techniques, which have so successfully validated acquired radio metric data for navigation purposes and have additionally served to rapidly pinpoint malfunctions in the tracking system, begin with the simple expedient of comparing each time-dependent radio metric data sample with a corresponding "predicted" value. To facilitate a discussion of the technique, the following notation is defined:

If

$$X(t) = \text{radio metric data type}$$

then

$$\Delta_X(t_i) \equiv X_A(t_i) - X_P(t_i)$$

where

$\Delta_X(t_i)$ = the "residual" of data type X at time t_i

$X_A(t_i)$ = acquired ("actual") data type X at time t_i

$X_P(t_i)$ = expected ("predicted") data type X at time t_i

If one has only a single or perhaps a few residuals during any particular time interval of interest, the amount of information that is yielded by this process is perforce severely limited. Basically, about the most that one can conclude with reasonable assurance is that:

Occurrence	Conclusion
Large residual	Invalid data
Small residual	Valid data, with the residual indicative of the magnitude of the prediction error

One of course strives to use accurate predictions in the process as it is the level of confidence in the predictions which determines what is "large" and what is "small" for the above. On the other hand, if one has a large population of residuals to work with, as is the usual case with the acquisition of both doppler and angular data, one can infer a great deal in addition to the above. These inferences can be broadly categorized as follows:

(1) *Signature.* By examining a large population of residuals, one can detect patterns ("signatures") of various types of systematic tracking system malfunctions. A prime example of this effect would be an error in the station time standard.

(2) *Noise.* By examining the standard deviation ("noise") of a large population of residuals (after a least squares curve fit), one can detect tracking system malfunctions which result in random errors. A prime example of this effect would be a failure of the doppler resolver counter.

As has already been stated, the above procedures have worked very well indeed for validating doppler data for navigation purposes as well as monitoring the health of the tracking system. It is now necessary to examine the applicability of the above techniques to Ranging System data (specifically the PRA).

III. Applicability of Current Near-Real-Time Radio Metric Data Validation Techniques to PRA Data

The PRA has been designed for use in cases where a very accurate estimate of the range at any given time already exists. The relationship between range and the output of the PRA is as follows:

$$R(t) = K[M(t)] + RPRA(t)$$
$$0 \leq RPRA(t) < K$$

where

$R(t)$ = range at time t

K = ambiguity resolution factor (a quantized input, in units of $R(t)$)

$M(t)$ = integer, determined from independent orbital knowledge

$RPRA(t)$ = "scaled" output of the PRA (i.e., in the same units as $R(t)$)

The ambiguity resolution factor K is extremely small when compared to the absolute range R, and in practice is selected (from 20 possible values) to be somewhat

[1] Differenced range vs integrated doppler. The name was chosen because one can discern a faint similarity between the relationship of "Pseudo-DRVID" to actual (PRA-produced) DRVID and of "Pseudo-Residuals" to actual (orbit-determination-produced) angle and doppler residuals.

larger than the current navigation estimate of the range uncertainty. It is not chosen indiscriminately larger than the range uncertainty as there is a penalty associated with increasingly large Ks (lengthened acquisition time).

In the past, it has always been somewhat blithely assumed that a "range" residual could be obtained from the PRA output and range predictions, and most probably it has been this assumption which has confused the issue of ranging system data validation and stymied efforts to approach the problem with differing viewpoints. The pith of the matter is:

> One cannot obtain a "range" residual from PRA output as one directly obtains doppler residuals from doppler data; one can only obtain, at best, a "PRA output" residual!

It is then necessary to inquire as to the composition and usefulness of a "PRA" residual; more specifically, one would like to determine what relationship the PRA residual bears to a range residual. The determination of this relationship is as follows:

Let the actual range at a time t_i be

$$R_A(t_i) \equiv K[M(t_i)] + RPRA_A(t_i)$$

so that a valid PRA acquisition would yield

$$RPRA(t_i) \cong RPRA_A(t_i)$$

(The above assumes that $RPRA_A$ is not within a few meters of 0 or K—this event having a very low probability of occurrence for typical acquisitions.)

Now assume that the predictions to be used have an error $Z(t_i)$ so that

$$R_P(t_i) \equiv K[M(t_i)] + RPRA_A(t_i) + Z(t_i)$$

One can now calculate a "predicted" PRA output

$$\begin{aligned} RPRA_P(t_i) &\equiv R_P(t_i) \text{ modulo } K \\ &= \{K[M(t_i)] + RPRA_A(t_i) + Z(t_i)\} \text{ modulo } K \end{aligned}$$

Having now obtained R_A, R_P, $RPRA_A$, and $RPRA_P$, one can construct a range residual and a corresponding PRA residual as follows:

$$\begin{aligned} \Delta_R(t_i) &\equiv R_A(t_i) - R_P(t_i) \\ &= \{K[M(t_i)] + RPRA_A(t_i)\} \\ &\quad - \{K[M(t_i)] + RPRA_A(t_i) + Z(t_i)\} \\ &= -Z(t_i) \end{aligned}$$

and

$$\begin{aligned} \Delta_{PRA}(t_i) &\equiv RPRA_A(t_i) - RPRA_P(t_i) \\ &= RPRA_A(t_i) \\ &\quad - \{K[M(t_i)] + RPRA_A(t_i) + Z(t_i)\} \text{ modulo } K \end{aligned}$$

$$= \begin{cases} -Z(t_i) & \\ \quad \text{if } 0 \leq RPRA(t_i) + Z(t_i) < K & \\ -Z(t_i) - JK & J = \text{integer} \\ \quad \text{if } RPRA(t_i) + Z(t_i) < 0 & \\ -Z(t_i) + JK & J = \text{integer} \\ \quad \text{if } RPRA(t_i) + Z(t_i) \geq K & \end{cases}$$

The final result is that:

$$\Delta_R(t_i) = \Delta_{PRA}(t_i) \text{ if } 0 \leq RPRA(t_i) + Z(t_i) < K$$

$$\Delta_R(t_i) \neq \Delta_{PRA}(t_i) \text{ if } RPRA(t_i) + Z(t_i) \begin{cases} < 0 \\ \geq K \end{cases}$$

Since K is selected on the basis of being only somewhat larger than the estimated uncertainty ($\approx Z(t_i)$), the inequality (above) will occur quite frequently, and hence there is no way that a PRA residual can be confidently equated to a range residual in near-real-time. Rendering the PRA residual even more useless in an absolute sense is the modulo character of the PRA data, which means that no matter how the PRA might malfunction, an "invalid" PRA residual statistically has an (averaged) 50% chance of being a smaller (magnitude) number than the corresponding "valid" PRA residual (assuming prediction accuracies are never significantly below the smallest possible K, or about 300 meters)—this property being in sharp contrast to the doppler and angle situation.

To illustrate with a very possible case, consider the following:

Let

$$K \equiv 18.2 \text{ km}$$

and

$$Z(t_i) \equiv 9.1 \text{ km}$$

Then

$$\Delta_R(t_i) = -9.1 \text{ km}$$

and

$$\Delta_{PRA}(t_i) = \begin{cases} -9.1 \text{ km if } RPRA(t_i) < 9.1 \text{ km} \\ +9.1 \text{ km if } RPRA(t_i) \geq 9.1 \text{ km} \end{cases}$$

The above results in the following:

(1) 50% chance of $\Delta_{PRA} \neq \Delta_R$.

(2) 50% chance of any random PRA output yielding a smaller absolute PRA residual than the correct PRA residual.

Finally, even if one could somehow obtain range residuals in near-real-time from PRA residuals, the powerful tool of examining a population of residuals for signature and noise, as is done with angle and doppler validation, would not be available because only a few PRA range acquisitions are normally made during a typical pass.

To recapitulate: past efforts to validate PRA data with the same techniques used so successfully to validate doppler and angle data were foreordained to failure because:

(1) It was falsely assumed that one could obtain range residuals, when in fact one can only obtain "PRA" residuals.

(2) Because of the very small (relative to absolute range) span of PRA output ($0 \leq$ PRA data $< K$), invalid (or random for that matter) PRA residuals are (on average) the same size as valid PRA residuals, thus to a considerable extent destroying the usefulness of a PRA residual—in marked contrast to the situation with doppler and angle residuals.

(3) Since few PRA measurements are usually made in any given pass, little "signature" or "noise" information would be available, even if range residuals could be reconstructed from PRA residuals in near-real-time.

IV. The Pseudo-DRVID Technique

It was shown in Section III that the technique of directly forming "actual" minus "predicted" residuals cannot be effectively applied to PRA data; the Pseudo-DRVID technique can be viewed as a slightly rearranged variation of the basic residual scheme, viz:

> Consider that two or more PRA ranging acquisitions are performed within a single pass. Allow the earliest PRA acquisition to be the "predict," which is updated to the time of a latter PRA ranging acquisition (the "actual") with ease and extreme accuracy by means of integrated doppler between the two PRA acquisitions. Using this process a "range" residual between the two PRA measurements can be formed which will include only the actual PRA data errors plus DRVID. Normally, the DRVID effect is on the order of meters[2], so that one might expect validation between the two acquisitions down to the several-meter level. The pivotal feature of this scheme is that it obviates the necessity for any orbital predictions, which is the very requirement that hamstrings the current techniques when applied to PRA data.

The derivation of the Pseudo-DRVID equations begins with the two way doppler equation

$$\begin{aligned} D2 = {} & 96\frac{240}{221}TSF_R \\ & - 96\,\frac{240}{221}TSF_T\left\{1-\frac{1}{c}\left[\left(\frac{dr}{dt}\right)_{up}+\left(\frac{dr}{dt}\right)_{dn}\right]\right\} \\ & + \text{bias} \end{aligned}$$

where

TSF_R = track synthesizer frequency (cps) at received time

TSF_T = track synthesizer frequency (cps) at transmitted time

$\left(\frac{dr}{dt}\right)_{up}$ = 2-way uplink range rate, m/s

$\left(\frac{dr}{dt}\right)_{dn}$ = 2-way downlink range rate, m/s

c = speed of light, m/s

bias = doppler bias frequency (cps), normally:
Block III receiver, 10^6 cps
Block IV receiver, 5×10^6 cps

[2]Except near solar conjunctions, when DRVID becomes 10s or 100s of meters.

However, during a ranging pass the TSF is not (usually) changed, so that

$$TSF_R = TSF_T$$

and

$$D2 = 96\frac{240}{221}\,TSF$$

$$-\,96\,\frac{240}{221}TSF\left\{1-\frac{1}{c}\left[\left(\frac{dr}{dt}\right)_{up}+\left(\frac{dr}{dt}\right)_{dn}\right]\right\}$$

$$+\ \text{bias}$$

$$=96\,\frac{240}{221}\left(\frac{TSF}{c}\right)\left[\left(\frac{dr}{dt}\right)_{up}+\left(\frac{dr}{dt}\right)_{dn}\right]+\text{bias}$$

or

$$D2-\text{bias}=96\,\frac{240}{221}\left(\frac{TSF}{c}\right)\left[\left(\frac{dr}{dt}\right)_{up}+\left(\frac{dr}{dt}\right)_{dn}\right]$$

Assuming that the difference in round trip range (RTR) is desired between the times t_a and t_b (and ignoring DRVID), one merely integrates the above equation as follows:

$$\int_{t_a}^{t_b}[D2-\text{bias}]\,dt$$

$$=\int_{t_a}^{t_b}96\frac{240}{221}\left(\frac{TSF}{c}\right)\left[\left(\frac{dr}{dt}\right)_{up}+\left(\frac{dr}{dt}\right)_{dn}\right]dt$$

defining

$CNTS(t)$ = doppler counter reading at time t, cycles

with

RTR = round trip range, m

$= r_{up} + r_{dn}$

r_{up} = uplink range, m

r_{dn} = downlink range, m

$$\left(\frac{dr}{dt}\right)_{up}=\frac{d}{dt}(r_{up})$$

$$\left(\frac{dr}{dt}\right)_{dn}=\frac{d}{dt}(r_{dn})$$

so that one has

$$\int_{t_a}^{t_b}(D2-\text{bias})\,dt=\int_{t_a}^{t_b}[D2]\,dt-\int_{t_a}^{t_b}(\text{bias})\,dt$$

$$\int_{t_a}^{t_b}(D2)\,dt = CNTS(t_b)-CNTS(t_a)$$

$$\int_{t_a}^{t_b}(\text{bias})\,dt=(t_b-t_a)\,(\text{bias})$$

and

$$\int_{t_a}^{t_b}96\frac{240}{221}\left(\frac{TSF}{c}\right)\left[\left(\frac{dr}{dt}\right)_{up}+\left(\frac{dr}{dt}\right)_{dn}\right]dt$$

$$=96\frac{240}{221}\left(\frac{TSF}{c}\right)\int_{t_a}^{t_b}\left[\left(\frac{dr}{dt}\right)_{up}+\left(\frac{dr}{dt}\right)_{dn}\right]dt$$

$$\int_{t_a}^{t_b}\left[\left(\frac{dr}{dt}\right)_{up}+\left(\frac{dr}{dt}\right)_{dn}\right]dt$$

$$=\int_{t_a}^{t_b}\left[\frac{d}{dt}(r_{up})+\frac{d}{dt}(r_{dn})\right]dt$$

$$=\int_{t_a}^{t_b}\frac{d}{dt}(r_{up}+r_{dn})\,dt$$

$$=\int_{t_a}^{t_b}d\,(r_{up}+r_{dn})=\int_{t_a}^{t_b}d\,(RTR)$$

$$=RTR(t_b)-RTR(t_a)$$

finally yielding

$$RTR(t_b)-RTR(t_a)$$

$$=\frac{CNTS(t_b)-CNTS(t_a)-\text{bias}\,(t_b-t_a)}{96\frac{240}{221}\left(\frac{TSF}{c}\right)}$$

Thus, simply by using the TSF, the doppler bias, and the doppler (cumulative) counter readings, one can rather easily and extremely accurately translate one range to a subsequent range, and hence be in a position to validate sequential PRA ranging acquisitions.

The complete algorithm is detailed below. It is essentially the equation above; however, it is presented in the form

$$\text{Pseudo-DRVID}=\Delta PRA(t_b,t_a)-\Delta DOP(t_b,t_a)$$

where

$$\Delta PRA(t_b, t_a) = \begin{cases} RPRA(t_b) - RPRA(t_a) \\ \text{if } RPRA(t_b) - RPRA(t_a) \geqq 0 \\ RPRA(t_b) - RPRA(t_a) + K \\ \text{if } RPRA(t_b) - RPRA(t_a) < 0 \end{cases}$$

and

$$\Delta DOP(t_b, t_a) = \begin{cases} [RTR(t_b) - RTR(t_a)] \text{ modulo } K \\ \quad \text{if } RTR(t_b) - RTR(t_a) \geqq 0 \\ [RTR(t_b) - RTR(t_a)] \text{ modulo } K + K \\ \quad \text{if } RTR(t_b) - RTR(t_a) < 0 \end{cases}$$

Additionally, doppler counter rollovers are accounted for, the explicit functional dependence of K upon the number of ranging components is displayed, and the quantities are scaled to be in meters.

Assume two PRA acquisitions at acquisition times of t_a and t_b and define

$PRTR(t)$ = PRA data in RU, for acquisition time $(T0) = t$

N = number of components

$RLOVRS$ = number of doppler counter "rollovers" between t_a and t_b

$K = K(N) = \frac{c}{48(TSF)}(2^{N+10})$

so that

$$\Delta PRA(t_b, t_a) = \frac{c}{48(TSF)}[PRTR(t_b) - PRTR(t_a) + Y]$$

where

$$Y = \begin{cases} 0 & \text{if } PRTR(t_b) - PRTR(t_a) \geq 0 \\ 2^{N+10} & \text{if } PRTR(t_b) - PRTR(t_a) < 0 \end{cases}$$

and

$$\Delta DOP(t_b, t_a) = \left\{ \frac{221}{96(240)} \left(\frac{c}{TSF}\right) [CNTS(t_b) - CNTS(t_a) + RLOVRS(10^{10}) - \text{bias}(t_b - t_a)] \right\} \text{modulo} \left[\left(\frac{c}{TSF}\right) \frac{2^{N+6}}{3} \right] + W$$

where

$$W = \begin{cases} 0 & \text{if } RTR(t_b) - RTR(t_a) \geqslant 0 \\ \left(\frac{c}{TSF}\right) \frac{2^{N+6}}{3} & \text{if } RTR(t_b) - RTR(t_a) < 0 \end{cases}$$

with the final result of

$$\text{Pseudo-DRVID} = \Delta PRA(t_b, t_a) - \Delta DOP(t_b, t_a)$$

V. Pseudo-DRVID Results

Tables 1 through 4 present results of applying the Pseudo-DRVID algorithm to selected Mariner 10 ranging passes. The tables are arranged to span the type of results possible (i.e., in terms of percent of valid acquisitions and degree of correspondence for the valid acquisitions) as follows:

Table	DSS	Date, 1975	Characterization of results
1	43	March 15	Excellent
2	63	March 15	Excellent
3	63	February 12	Fair
4	43	February 27	Poor

Table 5 presents some miscellaneous statistics for the data presented in the first four tables (it should be noted that all the Pseudo-DRVID results in Table 1 through 5 have been presented as absolute differences). The net result of the data presented in the tables is to show that the Pseudo-DRVID algorithm can validate good (sequential) PRA acquisitions by showing correspondence between acquisitions down to the 10-meter level.

VI. Conclusions

Past attempts at ranging system near-real-time data validation have generally been ineffective, primarily because the vast differences in the nature of ranging system data and, in particular, PRA ranging data, as compared to doppler and angular radio metric data, were not completely considered—thus leading to attempts to use techniques for ranging system data validation which are not really applicable. The "Pseudo-DRVID" technique presented here can validate sequential PRA acquisitions down to the 10-meter level and is now operational for near-real-time validation of PRA data.

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Table 1. Pseudo-DRVID PRA data validation, DSS 43, March 15, 1975

$(T0)^a_b$	$(T0)^a_a$	Pseudo-DRVID Meters	Pseudo-DRVID RU
Valid acquisitions			
21:15:00	20:30:00	5	17
23:25:00	22:00:00	7	23
00:55:00	00:10:00	2	8
02:50:00	01:40:00	9	32
06:00:00	03:45:00	5	19
Invalid acquisitions			
20:30:00[b]	19:45:00	272	953
04:30:00	03:45:00[b]	33,957	118,851
05:15:00	03:45:00[b]	287	1,004

[a]Times in GMT.
[b]The "good" acquisition of the pair.

Table 2. Pseudo-DRVID PRA data validation, DSS 63, March 15, 1975

$(T0)^a_b$	$(T0)^a_a$	Pseudo-DRVID Meters	Pseudo-DRVID RU
Valid acquisitions			
09:45:00	09:15:00	16	57
10:45:00	10:15:00	14	51
11:45:00	11:15:00	8	27
13:15:00	12:45:00	6	22
14:15:00	13:15:00	13	46
Invalid acquisitions			
12:15:00	11:45:00[b]	2,349	8,222
13:45:00	13:15:00[b]	40,406	141,421

[a]Times in GMT.
[b]The "good" acquisition of the pair.

Table 3. Pseudo-DRVID PRA data evaluation, DSS 63, February 12, 1975

$(T0)^a_b$	$(T0)^a_a$	Pseudo-DRVID Meters	Pseudo-DRVID RU
Valid acquisitions			
06:55:00	06:20:00	5	19
07:40:00	06:55:00	5	19
10:30:00	09:05:00	26	93
11:15:00	10:30:00	9	33
Invalid acquisitions			
08:30:00	07:40:00[b]	4,686	16,401
09:05:00[b]	08:30:00	8,765	30,676
09:45:00	09:05:00[b]	74,871	262,050
12:45:00	11:15:00[b]	23,408	81,929

[a]Times in GMT.
[b]The "good" acquisition of the pair.

Table 4. Pseudo-DRVID PRA data evaluation, DSS 43, February 27, 1975

$(T0)^a_b$	$(T0)^a_a$	Pseudo-DRVID Meters	Pseudo-DRVID RU
Valid acquisitions			
02:55:00	00:35:00	62	219
Invalid acquisitions			
00:35:00[b]	18:50:00	24,216	84,756
00:35:00[b]	20:30:00	23,336	81,676
00:35:00[b]	22:20:00	2,475	8,662
00:35:00[b]	23:30:00	60,738	212,584
01:45:00	00:35:00**	18,731	65,560
05:00:00	02:55:00**	10,347	36,214

[a]Times in GMT.
[b]The "good" acquisition of the pair.

Table 5. Pseudo-DRVID PRA evaluation statistics

Station	Date, 1975	Valid acquisitions Mean, m	Valid acquisitions Standard deviation, m
43	March 15	5.6	2.6
63	February 15	11.4	4.2
63	February 12	11.3	10.0
Combined above		9.3	6.2