The DOPPLER Evaluation Project

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1.0 Introduction:

DOPPLER satellite data, both Precise and Broadcast ephemeris, has been in use at Geodetic Survey of Canada since the late seventies. Recently, during the course of the NAD83 Continental Adjustment, it was decided that perhaps the weighting of variance-covariance data describing the accuracy of the X, Y, Z coordinates in a DOPPLER TAPE9 file was overly optimistic. Also, with the new capability of program GHOST to solve for auxiliary parameters, it was not clear which parameters would be most beneficial to solve for when adjusting DOPPLER data in the program. For these reasons, it was decided that some in-depth analysis of the data was required, resulting in the DOPPLER evaluation project.

The two main tasks of the evaluation were:

1. To evaluate and recommend scale factors to apply to variance-covariance matrices in the DOPPLER TAPE9 data input to future network adjustments.

2. To test and recommend auxiliary parameters to solve for Precise and Broadcast Ephemeris data in future network adjustments.

2.0 Procedure:

2.1 Tools:

1. Before evaluation adjustments, the data extracted from the DOPPAD file was transformed from the **NWL9D** (PRECISE EPHEMERIS) and **APL** (ASTRO PHYSICS LABORATORY, BROADCAST EPHEMERIS) systems to the **NAD83** (WGS84) system according to the following parameters:

$\Delta x = 0.0$
$\Delta y = 0.0$ { Translations
$\Delta z = +4.5$ metres

$\omega_x = 0.0$
$\omega_y = 0.0$ { Rotations
$\omega_z = +0.814$ arcseconds east

Δ scale = -0.6 ppm { Scale

Programs **"DOPTRN"** and **"SCTRANS"** were used to transform the DOPPLER data files. **"DOPTRN"** was used to transform the **binary** DOPPLER TAPE9 data files, and **"SCTRANS"** was used to transform the **ascii** DOPPLER data files.

2. Program **"GHOST"** was used to perform least squares adjustments of the DOPPLER data compiled for this evaluation.

2.2 Data Used in Evaluation:

Out of the approximately **400 TAPE9'S** on the **DOPPAD** file, only **195** were selected for this evaluation. It was decided that only the best configured, most reliable **DOPPLER** data would yield significant results. The **TAPE9'S** chosen were broken into 3 groups, namely:

1. **Precise:** **4** TAPE9'S, **158** stations, consisting of **1974,1975** and **1976 Precise** ephemeris data.

2. **"OSCAR":** **116** TAPE9'S, **514** stations, consisting of **1977-1981 Broadcast** ephemeris data.

3. **"NOVA":** **75** TAPE9'S, **554** stations, consisting of **1982-1986 Broadcast** ephemeris data.

The names **"OSCAR"** and **"NOVA"** were used for the last 2 groups because most of the satellites used in DOPPLER data collection during the 2 time frames were, respectively , **OSCAR** satellites from **1977** to **1981** and **NOVA** satellites from **1982** to **1986**. We wanted to test the 2 groups independently, to evaluate differences in their strength and in the orientation and scale.

2.21 Precise Framework Doppler:

Eleven adjustments were run, including the 1974, 1975, and 1976 Precise ephemeris data. Adjustment types ranged from those having no stations fixed , with no auxiliary parameters being solved for, to those having 3 stations fixed and solving for auxiliary parameters for each figure. The 3 stations that were fixed in some of the Precise data adjustments were: Yellowknife, N Sudbury and Kobau Astro. The stations were chosen due to their proximity to VLBI sites, and were fixed at NAD83 values computed in the July 1986 Continental Adjustment.

Auxiliary parameters solved for include ROTX, ROTY, ROTZ and SCPR in various combinations, where:

ROTX refers to rotation about the X axis. { in the CTS
ROTY refers to rotation about the Y axis. coordinate
ROTZ refers to rotation about the Z axis. system }
SCPR refers to space systems scale.

The 1st Precise adjustment, in which no constraints were applied, yielded coordinates which were later on used to constrain the OSCAR and NOVA adjustments. Geoid- ellipsoid separations and deflections (CODE9 cards) were not used in this adjustment #1, so that the heights appearing on the adjusted coordinates arising from it would be adjusted DOPPLER ellipsoid heights. This was necessary so that the elevations would be compatible with heights computed in the OSCAR and NOVA runs. It is important when fixing or constraining stations in a DOPPLER adjustment to have elevations compatible with DOPPLER computed values, to prevent large residuals.

Table 1 shows a summary of statistics from the Precise data adjustments.

2.22 Broadcast DOPPLER Data:

Before describing the OSCAR and NOVA runs, respectively, several terms used in the text should be explained:

"Constraining Stations" :

This refers to making use of GHOST "Constraint Equations" as an alternative to fixing stations in an adjustment. The technique is especially effective when adjusting DOPPLER data in program GHOST. Essentially, equations are written in terms of corrections to preliminary input coordinates. The corrections are in the local geodetic system, in the NORTH-SOUTH,EAST-WEST, and HEIGHT directions. The weights assigned to the corrections dictate the amount that the constrained station will move. By altering the weights it is possible to loosen or tighten constraints as required.

"Constraint Equations" :

A "Constraint Equation" consists of a set of 6 records for each station to be constrained: a GHOST format 93,92,and 97 code card and 3 GHOST format matrix input records containing the weights to be applied to the constraint. The format of the equations is detailed in a document prepared for DAAS entitled "Using Constraints in Program GHOST", by A.M.Lakanen and C. Parent, February 1988.

2.221 "OSCAR" Data:

Four adjustments were run , including Broadcast ephemeris data observed from 1977-1981. Adjustment types ranged from those having 43 fixed and 8 loosely constrained* stations, solving for no auxiliary parameters, to those having 51 constrained stations and solving for 232 auxiliary parameters. Stations were fixed or loosely constrained to values from Precise evaluation adjustment #1. Auxiliary parameters solved for include: ROTZ and SCPR , and were requested for each figure.

* constrained to 2 metres in X , Y and Z , using GHOST " Constraint Equations ".

Table 2 shows a summary of statistics from the OSCAR data adjustments.

2.22 "NOVA" Data:

Four adjustments were run, including Broadcast ephemeris data observed from 1982-1986. Adjustment types ranged from those having 73 fixed and 15 loosely constrained* stations, solving for no auxiliary parameters, to those having 52 constrained stations, solving for 150 auxiliary parameters. Stations were fixed or constrained to values from Precise adjustment #1. Auxiliary parameters solved for include: ROTZ and SCPR, and were requested for each figure.

* constrained to 2 metres in X , Y and Z , using GHOST " Constraint Equations ".

Table 3 shows a summary of statistics from the NOVA data adjustments.

3.0 Summary of Results:

The tables on the next 3 pages show pertinent statistics from the most significant GHOST adjustment for the Precise, "OSCAR", and "NOVA" groups respectively. Certain terminology used in the tables should be clarified:

Yr:

Refers to observation year, or year in which the DOPPLER observations were taken.

Fig:

Refers to a DOPPLER figure, where a figure is a group of stations observed using the same base stations. A figure may contain up to 15 stations.

3.1 Comments on Adjustment Results:

1. The variance factors from the Precise adjustments ranged from 3.3 to 4.3. The adjusted auxiliary parameter values were very small : in most cases they were less than their standard deviations.

2. The variance factors from the "OSCAR" adjustments ranged from 3.6 to 7.6.

3. The variance factors from the "NOVA" adjustments ranged from 5.2 to 10.6.

4. The absolute error ellipses arising from the adjustment were larger when auxiliary parameters were applied. Please see Appendix 2 for an example of this phemonemon.

5. Loosening constraints in a GHOST adjustment, by using "Constraint Equations", dramatically improved the variance factor. NOVA runs #1 and #2, and OSCAR runs #1 and #2 demonstrate this.

6. It was observed that the figures having only 2 constrained stations were significantly larger than those determined with figures having, say, 3 constrained stations. Figures with only 1 constrained station caused a singularity in the adjustment when an attempt was made to solve for auxiliary parameters for them.

3.2 Combined Adjustment:

Examining the statistics from the Precise adjustments in Table 1, it was noticeable that all of the variance factors from these adjustments gravitated around the value 3.5. Theoritically, then , we reasoned, scaling the covariance matrices for the Precise data by the value 3.5 in a GHOST adjustment should yield a variance factor of about 1.0: the "a priori" or ideal value.

The 2 most significant adjustments of the broadcast data were OSCAR run #4 and NOVA run #4 shown in Tables 2 and 3. The other runs of the broadcast data were unsuitable from which to make conclusions, in that they were either constrained too heavily to produce meaningful results, or else did not feature solving for auxiliary parameters . NOVA and OSCAR #4 suited our needs in both of these respects. Hence, we took an arithmetic mean of the variance factors from these 2 adjustments: 3.94 (OSCAR#4) and 6.23 (NOVA #4) and computed the value 5.1. Rather than working with such an awkward number, we chose a more round number: 5.0. By the same logic as with the Precise data, we reasoned that scaling the covariance data of both broadcast groups by 5.0 in a GHOST adjustment should yield an ideal variance factor of about 1.0.

To test the theoretical values of 3.5 and 5.0, another GHOST adjustment was performed, referred to as the " Combined Adjustment", including the Precise, OSCAR and NOVA data together. In the " Combined Adjustment " the Precise variance-covariance data was scaled by 3.5 and the OSCAR and NOVA variance-covariance by 5.0. [for more information regarding scaling covariance matrices using GHOST , please see **Appendix 1** entitled " **Scaling DOPPLER Variance-Covariance Matrices using GHOST** ", at the end of this report] . Auxiliary parameters ROTZ and SCPR were requested for each observation year of the broadcast data groups: 1977 to 1986 : 20 auxiliary parameters in all. It was not necessary to provide positional constraints, since the inclusion of the Precise data provided absolute positioning in the adjustment.

The results of the adjustment were rewarding and quite conclusive and are described in the next section.

3.21 Combined Adjustment Results:

FIXED STATIONS	TOTAL STATIONS	CONSTRAINED STATIONS	VARIANCE FACTOR	DEGREES OF FREEDOM	AUXILIARY PARAMETERS NUMBER	AUXILIARY PARAMETERS TYPE
0	1133	0	0.87	1645	20	ROTZ,SCPR FOR EACH YEAR OF B.E. DATA

The ideal value for the variance factor would have been 1.0. Hence, our variance factor of 0.87 showed us that we were at least in close proximity to the most ideal scale factors to use for Precise and broadcast ephemeris covariance data .

Since the value 0.87 was 13 % less than 1.0 (the ideal), we realized that the scale factors we had tentatively chosen were slightly higher than they should have been. Otherwise, the variance factor from our " combined adjustment " would have been greater than 1.0. Therefore, we decided that some modification of the numbers 3.5 and 5.0 was in order.

Re-examining the Precise adjustment summary results in Table 1, we noticed that Precise adjustment #1, the least constrained Precise data adjustment, yielded a variance factor of 3.37. We decided that this adjustment probably represented the most accurate picture of the behavior of the Precise data . Also, multiplying our tentative scale factor for the Precise data (3.5) by the variance factor from the combined adjustment (0.87) gave us a value of 3.04. Putting these 2 facts together, we decided that a more realisic scale factor for **Precise** ephemeris variance-covariance data would be **3.3** .

The picture for the broadcast data was not as clear. We realized that we had to lower the value 5.0 (since altering the Precise scale factor from 3.5 to 3.3 was not going to make a dramatic change) but by how much? Multiplying our tentative scale factor for the broadcast data (5.0) by the variance factor arising from the combined adjustment (0.87), we computed 4.35. Opting to err slightly on the cautious side, and to use a more round number, we finally decided that a more appropriate scale factor for **broadcast** ephemeris variance-covariance data would be **4.5** .

3.3 Error Ellipse Analysis:

It should be mentioned that relative and absolute error ellipses were requested in the final combined adjustment, and will be analyzed in depth at some future date. Time constraints did not permit analysis at this time. Regardless of the outcome of the pending error ellipses analysis, the decisions regarding the scale factors and auxiliary parameters would remain unchanged.

3.4 Auxiliary Parameter Analysis:

Benefitting from experience gained observing the behavior of auxiliary parameters and DOPPLER data in the NAD83 Continental Adjustment, we decided that out of auxiliary parameters ROTX, ROTY, ROTZ, and SCPR, the most significant results arose with ROTZ and SCPR. Hence, most of our tests on auxiliary parameters included these 2 parameters.

Solving first for separate auxiliary parameters ROTZ and SCPR for each figure, we finally realized that this was a bit redundant. We were't gaining information and we were loosing degrees of freedom with each parameter that was solved for. The final decision was to solve for auxiliary parameters more intelligently : 1 ROTZ and 1 SCPR for each observation year. Hence, in the final combined adjustment, we solved for ROTZ and SCPR for each year of broadcast data from 1977 to 1986 : 20 auxiliary parameters in all. We decided that solving for auxiliary parameters with the Precise data was pointless, since the adjusted parameters for the Precise data in most of our previous test adjustments were smaller than their standard deviations.

4.0 Conclusions:

1. The most significant results arose with auxiliary parameters ROTZ and SCPR and it was clear that solving for 2 auxiliary parameters for each figure is a waste of time. The auxiliary parameters for the Precise data were too small to even acknowledge.

2. The "OSCAR" and "NOVA" groups behaved in a similar fashion in our tests. Hence, broadcast ephemeris data between the years 1977-1981 and 1982-1987 should be treated equally regarding scale factor and auxiliary parameters. Our evaluation adjustments showed that Precise and broadcast data does not behave in a similar fashion, so the two groups should not be treated the same regarding scale factors and auxiliary parameters.

3. Absolute error ellipses are a measure of the accuracy of the adjusted coordinates from a least squares adjustment. Since in our tests the ellipses were larger when we applied auxiliary parameters, we decided that it is better not to over-indulge in the application of them. In other words, if they don't serve to significantly improve the adjustment, auxiliary parameters should not be included. A good example of this arose with the Precise data. Because the adjusted auxiliary parameter values arising from the adjustments were quite small (less than their standard deviations in most cases), we decided that Precise data shifted to the NAD83 system (as was done prior to this evaluation) should not have auxiliary parameters applied to it.

4. Loosening constraints in some of our test adjustments helped us to see the true picture of the behavior of DOPPLER data, whereas fixing stations (in other words, tightening constraining) resulted mostly in large variance factors. What appears to happen with fixing stations in a DOPPLER adjustment is the following: large residuals arise when the elevation on a station you are fixing in a GHOST adjustment is not compatible with the DOPPLER data. In this case, large residuals signal a problem where one might not exist.

5. Item # **6** in section **3.1** **"Comments on Adjustment Results"** posed a problem for us only because we initially solved for separate auxiliary parameters for each figure. Having only 1 constrained station in a figure should not pose a problem if you are grouping auxiliary parameters by year, as per our recommendations.

4.1 Recommendations:

1. Auxiliary Parameters:

   We recommend grouping DOPPLER projects by year, and solving for both ROTZ (rotation about the z axis) and SCPR (space systems scale) for each observation year of the **broadcast** ephemeris data. We don't recommend solving for auxiliary parameters for the NWL9D, or **Precise** ephemeris data that has been shifted to the NAD83 system.

2. Scale Factor for Precise Ephemeris Data:

   Based on the results of this evaluation, we are recommending that **Precise** ephemeris variance-covariance data should be scaled by the value **3.3**.

3. Scale Factor for Broadcast Ephemeris Data:

   Based on the results of this evaluation, we are recommending that **broadcast** ephemeris variance-covariance data should be scaled by the value **4.5**.

Appendix 1:

Scaling DOPPLER Variance-Covariance Matrices Using GHOST:

Since one of the purposes of this evaluation was to determine scale factor(s) by which **DOPPLER** coviance matrices could be scaled in the future, it is worthwhile to note the following: program **GHOST** now has the capability of applying a scale factor to **GPS** and **DOPPLER** covariance matrices. The option is invoked by entering the desired scale factor between columns **70** and **80** on the **97- code** card.

APPENDIX 2

EFFECT OF AUXILIARY PARAMETERS ON

ABSOLUTE ERROR ELLIPSES

PRECISE NAD83 DOPPLER GHOST ADJUSTMENT — MINOR = 6356752.3142

ELLIPSES ARE BASED ON THE APRIORI VARIANCE FACTOR OF 3.5224
RELATIVE ERROR (R.E.) = 2.45 X SEMI MAJOR AXIS / DISTANCE X 1000000

STATION NAME FROM	ORDER		STATION NAME TO	ORDER	DIST (KM)	AZIM (DEG)	STANDARD ERROR ELLIPSE AXES: SEMI MAJOR (DEG)	SEMI MAJOR (M)	SEMI MINOR (M)	RATIO MIN/MAJ	STANDARD DEVIATION: AZIMUTH R.E.	SPC	DISTANCE CLSM	CM		95% CONFIDENCE REGION
49183	(1)	141	569128	(1)	2.848	174	89	1.659	1.190	.72	119.9	581	419	119.4	1427	999 (5)
570005	(1)	140	57000	(1)	10.469	102	90	1.691	1.050	.62	21.4	103	159	166.9	396	999 (5)
65200	(1)	154	765140	(1)	61.776	184	90	1.453	.952	.66	4.8	23	15	95.6	58	120 (3)
544000	(1)	150	59504	(1)	74.075	281	91	1.102	.776	.70	2.2	10	15	109.5	36	50 (2)
74104	(1)	113	754010	(1)	57.330	326	91	1.029	.713	.69	3.4	16	15	83.5	44	50 (2)
6611	(1)	152	765046	(1)	103.869	62	90	.886	.578	.65	1.3	6	8	83.0	21	50 (2)

WITHOUT AUXILIARY PARAMETERS

PRECISE NAD83 DOPPLER GHOST ADJUSTMENT — MINOR = 6356752.3142

ELLIPSES ARE BASED ON THE APRIORI VARIANCE FACTOR OF 4.3431
RELATIVE ERROR (R.E.) = 2.45 X SEMI MAJOR AXIS / DISTANCE X 1000000

STATION NAME FROM	ORDER		STATION NAME TO	ORDER	DIST (KM)	AZIM (DEG)	STANDARD ERROR ELLIPSE AXES: SEMI MAJOR (DEG)	SEMI MAJOR (M)	SEMI MINOR (M)	RATIO MIN/MAJ	STANDARD DEVIATION: AZIMUTH R.E.	SPC	DISTANCE CLSM	CM		95% CONFIDEN REGION
749183	(1)	141	569128	(1)	2.848	174	87	2.173	1.339	.62	157.3	762	471	134.1	1869	999 (5)
570005	(1)	140	57000	(1)	10.469	102	87	2.954	1.225	.41	27.9	135	274	286.7	691	999 (5)
65200	(1)	154	765140	(1)	61.776	184	90	1.757	1.085	.62	5.9	28	18	108.9	70	120 (3)
44000	(1)	150	59504	(1)	74.075	281	90	1.530	.878	.57	2.5	12	20	151.3	51	120 (3)
674104	(1)	113	754010	(1)	57.330	326	89	1.392	.788	.57	4.5	21	18	101.4	59	120 (3)
26611	(1)	152	765046	(1)	103.869	62	91	1.049	.648	.62	1.5	7	9	97.4	25	50 (2)

WITH AUXILIARY PARAMETERS

Run #	Stations Fixed	Total Stations	Variance Factor	Degrees of Freedom	Auxiliary Parameters Number	Auxiliary Parameters Type
1	0	158	3.37	222	0	N/A
2	3	158	3.52	231	0	N/A
3	3	158	3.58	225	6	ROTZ,SCPR each yr
4	3	158	4.34	175	56	ROTZ,SCPR each fig
5	3	158	3.35	203	28	ROTX each fig
6	3	158	3.75	203	28	ROTY each fig
7	3	158	3.54	229	2	ROTZ,SCPR whole job
8	3	158	3.53	228	3	ROTZ each year
11	3	158	3.51	228	3	ROTY each year

Table 1

Summary of Precise DOPPLER Data GHOST Adjustments

Run #	Stations Fixed	Stations Constrained	Total Stations	Variance Factor	Degrees of Freedom	Auxiliary Parameters Number	Auxiliary Parameters Type
1	43	8	514	7.56	867	0	N/A
2	0	51	514	3.63	714	0	N/A
3	43	8	514	5.90	635	232	ROTZ,SCPR ea fig
4	0	51	514	3.94	482	232	ROTZ,SCPR ea fig

Table 2

Summary of "OSCAR" DOPPLER Data GHOST Adjustments

Run #	Stations Fixed	Stations Constrained	Total Stations	Variance Factor	Degrees of Freedom	Auxiliary Parameters Number	Auxiliary Parameters Type
1	37	15	554	10.62	606	0	N/A
2	0	52	554	5.24	450	0	N/A
3	37	15	554	8.63	456	150	ROTZ,SCPR ea fig
4	0	52	554	6.24	300	150	ROTZ,SCPR ea fig

Table 3

Summary of "NOVA" DOPPLER Data GHOST Adjustments