# 8 Combination and Comparison of Contributed Catalogs (SOL, SLB, DG)

The following section describes the preliminary catalogs submitted by seven different analysis centers using four independent software analysis packages, the construction of a combination catalog from seven contributed catalogs generated at seven different VLBI analysis centers, and comparisons of individual catalogs amongst themselves and the combined catalog. The main purpose of this analysis is to investigate systematic effects in individual solutions and estimate a precision of the combined and the individual realizations of the celestial reference frame.

## 8.1 Contributed Catalogs

The analysis centers involved in ICRF2 were asked to generate and submit two catalogs, one without the VCS sessions and one with the VCS sessions. The data and models used were to be as similar as possible. The VCS catalogs were to be used to construct a combination catalog at Main Astronomical Observatory. Lists of database sessions, sources to solve as arc parameters, and sources to exclude were distributed by GSFC. The solutions were to use group delays only, use only sources with three or more "good" observations, be a TRF solution using VTRF2008, and apply a no-net-rotation constraint using the 205 ICRF1 defining sources that were not classified as special handling sources. The solutions also were to solve for atmosphere gradients, apply pressure loading, use the VMF1 model, and apply thermal deformation. Seven analysis centers generated catalogs using four independent software analysis packages and submitted them in time for use in constructing a combination catalog. Table 3 lists the particulars of the contributed solutions. It can be seen that no two analysis centers used the same data span, the same sessions, or obtained the same number of estimated sources. One of the catalogs also had an editing problem and used some observations normally considered bad. Also, most analysis centers used different analysis models. Some did not use the thermal deformation model, or the VMF1 model, or pressure loading, or solved for baselines instead of the TRF. The model comparisons section showed that these analysis differences should not produce any significant systematic differences, but may increase the noise level of the differences between solutions. Seven contributed catalogs were used to produce the combined catalog, listed with an "*" in Table 3. Because of larger differences seen in the aus007a solution, the Geoscience Australia group produced two additional solutions, aus008a and aus009a, which are included in the comparisons later in this section. Later, in §10, we will present comparisons of the corresponding TRF and EOP solutions.

## 8.2 Creation of a Combined Catalog

The seven catalogs used to generate a combination catalog are given in Table 4. The first line is the combination catalog itself, designated maoC08a. There are two columns for the number of sources. The first gives the number of sources in the catalog and the second gives the number of sources included in the combination catalog and used in the comparisons.

In the combination procedure, only sources which were observed three or more times (number of group delays) were used. The procedure was performed recursively, eliminating outlier radio sources ($5\sigma$) from individual catalogs. The outliers are sources with small ($3 - 15$) numbers of observations in one or two sessions with poor network configuration

Table 3: Contributed Catalogs

| Solution ID | # Sessions | # Sources | Time Range | Software | Analysis Center |
|---|---|---|---|---|---|
| aus007a* | 3712 | 1564 | 1979.7-2008.7 | OCCAM6.2 | GA |
| aus008a | 3774 | 2869 | 1979.7-2008.7 | OCCAM6.2 | GA |
| aus009a | 3774 | 537 | 1979.7-2008.7 | OCCAM6.2 | GA |
| bkg001a* | 3823 | 3039 | 1984.0-2009.2 | CALC 10, SOLVE rev. 2007.10.31 | BKG |
| gsf007a | 4516 | 1219 | 1979.7-2009.2 | CALC 10, SOLVE rev. 2008.12.05 | GSFC |
| gsf007b* | 4540 | 3414 | 1979.7-2009.2 | CALC 10, SOLVE rev. 2008.12.05 | GSFC |
| iaa008a | ... | 3009 | 1980.0-2009.2 | QUASAR | IAA |
| iaa008b | ... | 3009 | 1980.0-2009.2 | QUASAR | IAA |
| iaa008c* | ... | 3009 | 1980.0-2009.2 | QUASAR | IAA |
| mao008a* | 4541 | 3555 | 1979.7-2009.3 | SteelBreeze | MAO |
| opa008b* | 4528 | 3244 | 1979.7-2009.2 | CALC 10, SOLVE rev. 2008.12.05 | OP |
| opa008c | 4434 | 1188 | 1979.7-2009.2 | CALC 10, SOLVE rev. 2008.12.05 | OP |
| usn010b* | 4465 | 3414 | 1979.7-2009.2 | CALC 10, SOLVE rev. 2007.11.08 | USNO |

Table 4: General characteristics of the combination catalog and the seven contributed solutions used to construct it.

| Solution ID | $N_{sources}$ total | $N_{sources}$ in comb. | Software | Analysis Center |
|---|---|---|---|---|
| maoC08a | 3572 | 3572 | Combination | MAO |
| aus007a | 1564 | 1516 | OCCAM6.2 | GA |
| bkg001a | 3019 | 2978 | CALC/SOLVE | BKG |
| gsf007b | 3414 | 3378 | CALC/SOLVE | GSFC |
| iaa008c | 2961 | 2918 | QUASAR | IAA |
| mao008a | 3555 | 3512 | SteelBreeze | MAO |
| opa008b | 3244 | 3214 | CALC/SOLVE | OP |
| usn010b | 3414 | 3380 | CALC/SOLVE | USNO |

(usually, one-baseline sessions). The combined catalog, maoC08a, consists of the coordinates of 3572 radio sources. The combined solution, maoC08a, was created using the arc-length method. The method of arc-lengths was developed at the Main Astronomical Observatory of the National Academy of Sciences of Ukraine and is described in Kur′yanova & Yatskiv [1993]. The principles of the arc-length method are:

- calculation of the arc lengths (distances on the celestial sphere) of the common ICRF1 defining sources for all individual solutions;
- construction of an intermediate reference frame, with an orientation defined by the positions of two radio sources;
- building of a combined catalog in the intermediate reference frame;
- transition from the combined catalog frame of two sources to a frame given by the positions of the ICRF1 defining radio sources.

The list of ICRF1 defining sources used consisted of 204 objects. From the 212 ICRF1 defining sources we eliminated eight sources: seven are from the special handling sources list (0014+813, 0235+164, 0637−752, 0738+313, 1308+326, 1448+762 and 2145+067) plus the source 1903−802, which is missing in bkg001a solution.

## 8.3 Comparison of Individual Solutions

A comparison of catalogs was performed in the following way. First, the parameters of a transformation model between two catalogs were esti-

mated with the least-squares method. Then, the model was applied to coordinates of one of the catalogs and wrms residuals for right ascension and declination were calculated. And lastly, from the comparison of three catalogs at a time (combined and the two individual ones), the so-called "external" dispersions have been evaluated.

### 8.3.1 Systematic Effects

For evaluation of systematic effects a transformation model was applied. The model assumes the following systematic effects: rotation of one catalog relative to another, slopes in Right Ascension and declination, a bias in declination, and harmonic terms in both coordinates (see Bolotin & Lytvyn [2008]). The differences in Right Ascension, $\Delta\alpha$, and declination, $\Delta\delta$, are presented as:

$$\Delta\alpha = A_1 \tan\delta \cos\alpha + A_2 \tan\delta \sin\alpha - A_3 + D_\alpha(\delta - \delta_0) + C_\alpha \sin(\alpha + \varphi_\alpha) \quad (2)$$

$$\Delta\delta = -A_1 \sin\alpha + A_2 \cos\alpha + D_\delta(\delta - \delta_0) + B_\delta + C_\delta \sin(\alpha + \varphi_\delta), \quad (3)$$

where $A_1$, $A_2$ and $A_3$ are the rotation angles about the three axes; $D_\alpha$ and $D_\delta$ are the slopes in right ascension and declination as functions of the declination; $B_\delta$ is a bias in declination; $C_\alpha$, $\varphi_\alpha$ and $C_\delta$, $\varphi_\delta$ are amplitudes and phases of harmonic oscillations in right ascension and declination.

Table 5: Number of common sources in the catalogs (all and defining).

| ID | aus008a | | aus009a | | bkg001a | | gsf007b | | iaa008c | | mao008a | | opa008b | | usn010b | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| maoC08a | 2847 | 203 | 536 | 177 | 2977 | 204 | 3375 | 204 | 2918 | 204 | 3505 | 204 | 3214 | 204 | 3377 | 204 |
| aus008a | | | 537 | 177 | 2736 | 203 | 2836 | 203 | 2583 | 203 | 2829 | 203 | 2804 | 203 | 2839 | 203 |
| aus009a | | | | | 536 | 177 | 536 | 177 | 536 | 171 | 536 | 177 | 536 | 177 | 536 | 177 |
| bkg001a | | | | | | | 2945 | 204 | 2747 | 204 | 2933 | 204 | 2883 | 204 | 2945 | 204 |
| gsf007b | | | | | | | | | 2897 | 204 | 3340 | 204 | 3202 | 204 | 3367 | 204 |
| iaa008c | | | | | | | | | | | 2899 | 204 | 2848 | 204 | 2898 | 204 |
| mao008a | | | | | | | | | | | | | 3193 | 204 | 3345 | 204 |
| opa008b | | | | | | | | | | | | | | | 3209 | 204 |

To calculate the parameters of the model the coordinates of the common (for both catalogs) ICRF1 defining sources were used. Then, after the model was applied, the wrms was evaluated for the entire set of common radio sources. The numbers of common defining sources and all sources for each pair of catalogs are presented in Table 5.

Table 6: Weighted post-fit residuals ($\Delta\alpha\cos\delta$, $\Delta\delta$), $\mu as$.

| ID | aus008a | | aus009a | | bkg001a | | gsf007b | | iaa008c | | mao008a | | opa008b | | usn010b | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| maoC08a | 103 | 127 | 57 | 59 | 39 | 37 | 27 | 30 | 45 | 42 | 43 | 54 | 27 | 39 | 27 | 41 |
| aus008a | | | 26 | 19 | 129 | 128 | 104 | 109 | 108 | 115 | 98 | 102 | 106 | 108 | 115 | 110 |
| aus009a | | | | | 66 | 68 | 58 | 58 | 60 | 69 | 53 | 56 | 58 | 58 | 64 | 62 |
| bkg001a | | | | | | | 40 | 39 | 47 | 46 | 59 | 61 | 42 | 42 | 42 | 69 |
| gsf007b | | | | | | | | | 49 | 64 | 41 | 46 | 15 | 15 | 24 | 29 |
| iaa008c | | | | | | | | | | | 59 | 52 | 46 | 40 | 49 | 49 |
| mao008a | | | | | | | | | | | | | 41 | 46 | 46 | 55 |
| opa008b | | | | | | | | | | | | | | | 24 | 28 |

The results of least square estimation of model parameters are presented in Table 7 and Table 8. Table 7 shows comparison of the combined catalog, maoC08a, with the individual solutions. Mutual comparisons between individual solutions are presented in Table 8. In the tables the first lines for each pair of catalogs present the estimated values, and the second lines present the standard deviations. Parameters $A_1$, $A_2$, $A_3$,

Table 7: Comparison of catalogs: maoC08a vs. individual solutions. The first row for each pair presents the estimated parameters of the transformation model. The second rows present the corresponding standard deviations.

| $A_1$ | $A_2$ | $A_3$ | $D_\alpha$ | $D_\delta$ | $B_\delta$ | $C_\alpha$ | $\varphi_\alpha$ | $C_\delta$ | $\varphi_\delta$ |
|---|---|---|---|---|---|---|---|---|---|
| maoC08a – aus008a | | | | | | | | | |
| 290.5 | 111.4 | −164.5 | −37.8 | 37.8 | −23.3 | 13.0 | 301.7 | 32.3 | 18.5 |
| 20.1 | 16.6 | 11.6 | 21.3 | 13.1 | 10.6 | 15.2 | 65.1 | 22.1 | 37.4 |
| maoC08a – aus009a | | | | | | | | | |
| 29.0 | 8.1 | −11.6 | −26.1 | −8.0 | 18.4 | 12.8 | 261.5 | 35.7 | 353.8 |
| 10.9 | 9.8 | 7.5 | 12.6 | 7.8 | 6.9 | 9.3 | 40.0 | 12.5 | 18.6 |
| maoC08a – bkg001a | | | | | | | | | |
| −34.2 | 13.9 | −14.4 | −5.2 | 13.0 | −30.0 | 9.2 | 146.3 | 13.2 | 128.3 |
| 6.8 | 6.0 | 4.1 | 7.2 | 4.8 | 4.3 | 5.0 | 34.9 | 7.7 | 30.6 |
| maoC08a – gsf007b | | | | | | | | | |
| −1.2 | −3.4 | 0.3 | −0.9 | 11.2 | −2.2 | 8.9 | 185.8 | 1.8 | 79.5 |
| 5.2 | 4.6 | 3.3 | 5.6 | 3.5 | 3.1 | 4.2 | 27.1 | 5.3 | 181.4 |
| maoC08a – iaa008c | | | | | | | | | |
| −7.1 | 11.9 | 5.0 | 21.3 | −16.7 | 2.5 | 7.5 | 225.8 | 9.4 | 305.8 |
| 7.8 | 6.9 | 5.1 | 8.6 | 5.4 | 4.8 | 6.8 | 46.3 | 8.8 | 49.2 |
| maoC08a – mao008a | | | | | | | | | |
| 8.8 | −25.3 | −6.6 | 1.1 | −24.5 | 24.5 | 19.2 | 148.7 | 7.2 | 53.3 |
| 8.8 | 7.9 | 6.0 | 9.7 | 5.9 | 5.3 | 7.1 | 23.9 | 9.1 | 81.6 |
| maoC08a – opa008b | | | | | | | | | |
| 9.6 | −11.8 | 2.3 | −0.8 | 18.6 | −12.1 | 5.4 | 191.5 | 6.3 | 73.3 |
| 6.3 | 5.6 | 4.1 | 6.8 | 4.2 | 3.7 | 5.2 | 54.6 | 6.5 | 65.4 |
| maoC08a – usn010b | | | | | | | | | |
| −6.3 | 26.4 | 7.4 | 2.7 | 3.6 | −1.6 | 33.7 | 350.5 | 18.2 | 259.5 |
| 6.5 | 5.7 | 4.2 | 7.0 | 4.5 | 4.0 | 5.2 | 9.2 | 6.7 | 23.3 |

$B_\delta$, $C_\alpha$ and $C_\delta$ are in units of $\mu as$; units for $D_\alpha$ and $D_\delta$ are $\mu as/rad$; and phases $\varphi_\alpha$ and $\varphi_\delta$ are in degrees.

In Table 6 weighted post-fit residuals for each comparison pair are shown. The residuals have been evaluated for each pair of catalogs after removing the estimated systematic effects.

As one can see from the tables, there are significant systematic effects in catalog aus008a. The angles of rotation are about 150–300 $\mu$as between aus008a and other individual solutions, while for other individual catalogs (including aus009a) the mutual rotation is about 50 $\mu$as or less. Also, standard deviations of estimated parameters for catalog aus008a are greater than the corresponding deviations of parameters for other solutions by about 2–3 times.

On the other hand, catalog aus009a shows relatively good agreement with the other individual catalogs. Catalogs aus008a and aus009a differ only in the minimum number of observations per source ($> 3$ for aus008a and $> 100$ for aus009a, which eliminated many VCS sources). This could indicate the influence of *a priori* information on results in solutions obtained by Geoscience Australia caused either by design of the least squares collocation method or its implementation. In any case, if catalog aus008a is omitted, then the remaining mutual systematic effects between seven individual catalog solutions obtained with four independent software packages do not exceed the 50 $\mu$as level.

Also we note considerably large (up to 40 $\mu$as) angles of rotation between the bkg001a catalog and other individual solutions. The reason of this change in orientation is the absence of one ICRF1 defining source, 1903−802, in the BKG solution. All the other analysis centers included observations of this source and its *a priori* coordinates were used in the

Table 8: Comparison of catalogs: comparisons between individual solutions. The first rows of each comparison present the estimated parameters of the transformation model. The second rows present the corresponding standard deviations.

| $A_1$ | $A_2$ | $A_3$ | $D_\alpha$ | $D_\delta$ | $B_\delta$ | $C_\alpha$ | $\varphi_\alpha$ | $C_\delta$ | $\varphi_\delta$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | aus008a – aus009a | | | | | |
| −266.4 | −109.7 | 146.7 | 11.0 | −18.3 | 22.5 | 12.3 | 138.8 | 4.0 | 234.8 |
| 4.1 | 3.5 | 2.5 | 4.5 | 2.8 | 2.3 | 3.1 | 14.9 | 4.1 | 67.8 |
| | | | | aus008a – bkg001a | | | | | |
| −332.9 | −106.2 | 155.3 | 39.1 | −21.0 | −9.9 | 27.2 | 118.7 | 43.4 | 167.2 |
| 21.9 | 18.4 | 12.7 | 23.4 | 14.6 | 11.8 | 16.6 | 34.1 | 25.5 | 28.9 |
| | | | | aus008a – gsf007b | | | | | |
| −289.4 | −114.7 | 162.3 | 33.9 | −22.5 | 19.8 | 16.0 | 154.5 | 28.4 | 190.6 |
| 18.1 | 15.1 | 10.5 | 19.3 | 11.9 | 9.7 | 13.3 | 49.8 | 20.4 | 37.9 |
| | | | | aus008a – iaa008c | | | | | |
| −287.9 | −97.9 | 165.4 | 60.0 | −63.5 | 32.1 | 18.2 | 146.7 | 24.7 | 236.5 |
| 19.0 | 15.9 | 11.1 | 20.3 | 12.6 | 10.3 | 14.1 | 45.9 | 19.2 | 50.7 |
| | | | | aus008a – mao008a | | | | | |
| −277.4 | −138.2 | 158.3 | 41.5 | −71.8 | 59.6 | 25.9 | 134.2 | 23.2 | 153.0 |
| 16.9 | 14.1 | 10.0 | 18.1 | 11.1 | 9.1 | 12.8 | 28.5 | 19.6 | 41.9 |
| | | | | aus008a – opa008b | | | | | |
| −277.8 | −120.3 | 162.9 | 33.7 | −13.8 | 7.9 | 14.4 | 154.3 | 25.0 | 190.3 |
| 18.2 | 15.1 | 10.6 | 19.3 | 11.9 | 9.7 | 13.3 | 55.3 | 20.5 | 43.1 |
| | | | | aus008a – usn010b | | | | | |
| −292.9 | −85.4 | 167.9 | 36.6 | −21.1 | 11.3 | 26.1 | 1.0 | 46.3 | 226.7 |
| 19.1 | 15.9 | 11.1 | 20.3 | 12.6 | 10.2 | 13.8 | 32.3 | 19.6 | 26.7 |
| | | | | aus009a – bkg001a | | | | | |
| −59.4 | 10.3 | −0.4 | 25.8 | 20.5 | −48.4 | 18.0 | 120.6 | 41.1 | 166.7 |
| 12.4 | 11.3 | 8.6 | 14.6 | 9.3 | 8.2 | 9.7 | 35.3 | 14.5 | 18.5 |
| | | | | aus009a – gsf007b | | | | | |
| −31.1 | −13.4 | 10.2 | 23.1 | 16.3 | −17.8 | 14.6 | 109.1 | 38.1 | 167.7 |
| 10.7 | 9.7 | 7.4 | 12.6 | 8.0 | 7.1 | 8.5 | 37.1 | 12.5 | 17.2 |
| | | | | aus009a – iaa008c | | | | | |
| −34.7 | 4.6 | 18.6 | 50.4 | −10.1 | −15.7 | 7.6 | 124.3 | 28.9 | 192.3 |
| 12.0 | 10.9 | 8.4 | 14.1 | 8.9 | 8.0 | 9.4 | 82.2 | 13.3 | 27.0 |
| | | | | aus009a – mao008a | | | | | |
| −23.4 | −39.0 | 2.3 | 23.7 | −17.1 | 6.6 | 26.6 | 111.8 | 38.7 | 156.3 |
| 10.0 | 9.2 | 7.1 | 11.9 | 7.5 | 6.7 | 8.1 | 19.6 | 12.0 | 15.7 |
| | | | | aus009a – opa008b | | | | | |
| −19.6 | −24.4 | 12.7 | 23.8 | 21.9 | −26.2 | 12.9 | 86.1 | 38.8 | 157.6 |
| 10.7 | 9.8 | 7.5 | 12.6 | 8.0 | 7.1 | 9.1 | 40.2 | 12.7 | 16.7 |
| | | | | aus009a – usn010b | | | | | |
| −39.4 | 18.9 | 18.4 | 27.9 | 6.9 | −15.7 | 36.8 | 17.8 | 46.6 | 198.1 |
| 11.6 | 10.5 | 8.0 | 13.6 | 8.7 | 7.7 | 10.2 | 14.5 | 12.6 | 16.4 |
| | | | | bkg001a – gsf007b | | | | | |
| 29.9 | −19.3 | 14.9 | 4.0 | −3.5 | 30.0 | 2.6 | 257.7 | 8.4 | 308.9 |
| 6.6 | 6.1 | 4.3 | 7.6 | 5.3 | 4.7 | 5.5 | 115.2 | 7.9 | 49.2 |
| | | | | bkg001a – iaa008c | | | | | |
| 25.1 | −4.2 | 19.7 | 24.5 | −31.2 | 34.4 | 10.8 | 287.3 | 19.5 | 306.8 |
| 7.8 | 7.1 | 5.2 | 9.0 | 6.1 | 5.4 | 6.3 | 35.5 | 9.2 | 24.8 |
| | | | | bkg001a – mao008a | | | | | |
| 36.0 | −44.0 | 5.7 | 2.0 | −37.7 | 54.8 | 12.1 | 120.8 | 4.6 | 358.1 |
| 10.1 | 9.3 | 6.9 | 11.6 | 7.8 | 6.9 | 7.9 | 42.9 | 11.6 | 140.8 |

(continued on next page)

(Table 8: continued)

| $A_1$ | $A_2$ | $A_3$ | $D_\alpha$ | $D_\delta$ | $B_\delta$ | $C_\alpha$ | $\varphi_\alpha$ | $C_\delta$ | $\varphi_\delta$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | bkg001a – opa008b | | | | | |
| 41.4 | −29.0 | 17.8 | 5.4 | 2.5 | 21.2 | 5.2 | 323.4 | 6.9 | 351.8 |
| 6.9 | 6.4 | 4.6 | 7.9 | 5.5 | 4.8 | 5.4 | 65.5 | 8.1 | 63.8 |
| | | | | bkg001a – usn010b | | | | | |
| 22.9 | 11.0 | 22.0 | 7.2 | −11.7 | 30.6 | 41.7 | 351.6 | 26.7 | 269.9 |
| 7.5 | 6.8 | 4.9 | 8.5 | 6.0 | 5.3 | 6.0 | 8.4 | 8.4 | 18.5 |
| | | | | gsf007b – iaa008c | | | | | |
| −5.2 | 15.2 | 5.6 | 22.6 | −26.6 | 3.5 | 7.7 | 297.1 | 11.1 | 302.6 |
| 7.1 | 6.4 | 4.9 | 8.2 | 5.5 | 4.9 | 5.6 | 46.7 | 8.3 | 39.3 |
| | | | | gsf007b – mao008a | | | | | |
| 7.9 | −23.1 | −7.1 | 1.7 | −36.2 | 27.0 | 13.7 | 122.5 | 4.7 | 71.8 |
| 7.3 | 6.7 | 5.1 | 8.4 | 5.6 | 5.0 | 5.8 | 28.2 | 8.0 | 103.7 |
| | | | | gsf007b – opa008b | | | | | |
| 10.9 | −9.5 | 2.6 | 0.6 | 6.0 | −8.6 | 4.5 | 359.0 | 5.6 | 74.7 |
| 2.5 | 2.3 | 1.7 | 2.9 | 1.9 | 1.7 | 2.1 | 26.4 | 2.7 | 29.9 |
| | | | | gsf007b – usn010b | | | | | |
| −7.1 | 30.5 | 7.6 | 3.9 | −7.8 | 0.9 | 41.3 | 355.1 | 20.9 | 255.1 |
| 4.5 | 4.1 | 3.0 | 5.2 | 3.6 | 3.1 | 3.7 | 5.2 | 4.9 | 14.4 |
| | | | | iaa008c – mao008a | | | | | |
| 12.4 | −38.7 | −14.1 | −23.8 | −7.1 | 21.7 | 21.8 | 119.3 | 16.3 | 113.9 |
| 9.3 | 8.5 | 6.6 | 10.8 | 7.1 | 6.3 | 7.5 | 22.4 | 10.9 | 35.9 |
| | | | | iaa008c – opa008b | | | | | |
| 16.6 | −25.1 | −3.2 | −22.1 | 33.2 | −12.7 | 6.7 | 79.5 | 15.3 | 106.3 |
| 7.2 | 6.6 | 5.0 | 8.4 | 5.5 | 4.9 | 6.3 | 51.3 | 8.3 | 30.0 |
| | | | | iaa008c – usn010b | | | | | |
| −2.6 | 15.9 | 1.9 | −18.9 | 18.0 | −2.0 | 37.4 | 5.4 | 16.5 | 224.5 |
| 8.4 | 7.6 | 5.8 | 9.7 | 6.5 | 5.8 | 7.2 | 10.7 | 8.9 | 34.3 |
| | | | | mao008a – opa008b | | | | | |
| 2.2 | 13.4 | 9.2 | −2.1 | 43.8 | −37.0 | 16.4 | 316.9 | 1.1 | 124.7 |
| 7.2 | 6.7 | 5.1 | 8.4 | 5.5 | 4.9 | 5.8 | 23.7 | 8.6 | 399.4 |
| | | | | mao008a – usn010b | | | | | |
| −14.7 | 53.6 | 15.6 | 3.6 | 29.7 | −27.0 | 50.6 | 342.0 | 25.3 | 255.0 |
| 8.5 | 7.8 | 6.0 | 9.9 | 6.6 | 5.9 | 7.1 | 8.6 | 9.4 | 22.7 |
| | | | | opa008b – usn010b | | | | | |
| −17.5 | 39.9 | 5.1 | 3.5 | −13.6 | 9.3 | 37.0 | 354.1 | 26.2 | 255.9 |
| 4.4 | 4.1 | 3.0 | 5.1 | 3.5 | 3.1 | 3.7 | 5.8 | 4.9 | 11.4 |

no-net-rotation constraints to fix the orientation of the obtained celestial reference frame.

Significant differences in the harmonic oscillation parameters are obtained for the usn010b catalog. Comparing with gsf007b, they are $41 \pm 4\,\mu$as and $21 \pm 5\,\mu$as for Right Ascension and declination respectively. Such deformations could be caused either by the absence of diurnal and semi-diurnal tidal EOP variations or by using an obsolete model of nutation (see Bolotin [2007]).

### 8.3.2 External Uncertainties

The so-called "external" uncertainties can be evaluated in the following way. For a pair of catalogs we can write (with some assumptions):

$$\overline{d_{12}{}^2} = {\sigma_1}^2 - 2\rho_{12}\sigma_1\sigma_2 + {\sigma_2}^2 \tag{4}$$

where $\overline{d_{12}{}^2}$ is the weighted mean of the squared differences between a pair of catalogs; $\sigma_1$ and $\sigma_2$ are the "external" uncertainties of the catalogs; and $\rho_{12}$ is the corresponding correlation coefficient. By writing such equations for three catalogs, it is possible to construct a system of equations and to solve it with respect to $\sigma_1$, $\sigma_2$ and $\sigma_3$. The results of such calculations of external uncertainties are presented in Table 9. In these comparisons the combined solution has been used as third catalog. The calculations were done for all common radio sources in the three catalogs.

"External" uncertainties for almost all catalogs except bkg001a, aus008a, and aus009a are at the level of 50 $\mu$as. For bkg001a they are about twice as great, and for aus009a catalog they are about 1.5 times greater. So, in addition to the systematic effects, these catalogs are also noisier.

Table 9: Comparison of catalogs: external uncertainties

| Coordinate | index | | $\sigma_1$ | $\sigma_2$ | $\sigma_3$ |
|---|---|---|---|---|---|
| | 1 | 2 | $\mu as$ | $\mu as$ | $\mu as$ |
| $\alpha$ | aus008a | aus009a | 58 | 61 | 6 |
| $\delta$ | aus008a | aus009a | 73 | 76 | 3 |
| $\alpha$ | aus008a | bkg001a | 188 | 89 | 14 |
| $\delta$ | aus008a | bkg001a | 220 | 73 | 7 |
| $\alpha$ | aus008a | gsf007b | 189 | 22 | 10 |
| $\delta$ | aus008a | gsf007b | 223 | 29 | 6 |
| $\alpha$ | aus008a | iaa008c | 192 | 64 | 14 |
| $\delta$ | aus008a | iaa008c | 219 | 70 | 6 |
| $\alpha$ | aus008a | mao008a | 199 | 57 | 17 |
| $\delta$ | aus008a | mao008a | 227 | 62 | 10 |
| $\alpha$ | aus008a | opa008b | 190 | 20 | 10 |
| $\delta$ | aus008a | opa008b | 224 | 30 | 6 |
| $\alpha$ | aus008a | usn010b | 190 | 23 | 11 |
| $\delta$ | aus008a | usn010b | 223 | 40 | 8 |
| $\alpha$ | aus009a | bkg001a | 58 | 24 | 9 |
| $\delta$ | aus009a | bkg001a | 77 | 27 | 5 |
| $\alpha$ | aus009a | gsf007b | 57 | 15 | 7 |
| $\delta$ | aus009a | gsf007b | 75 | 18 | 3 |
| $\alpha$ | aus009a | iaa008c | 57 | 33 | 11 |
| $\delta$ | aus009a | iaa008c | 76 | 36 | 4 |
| $\alpha$ | aus009a | mao008a | 56 | 38 | 11 |
| $\delta$ | aus009a | mao008a | 73 | 42 | 7 |
| $\alpha$ | aus009a | opa008b | 57 | 15 | 6 |
| $\delta$ | aus009a | opa008b | 75 | 16 | 3 |

(continued on next page)

(Table 9: continued)

| Coordinate | index | | $\sigma_1$ | $\sigma_2$ | $\sigma_3$ |
|---|---|---|---|---|---|
| | 1 | 2 | $\mu as$ | $\mu as$ | $\mu as$ |
| $\alpha$ | aus009a | usn010b | 57 | 17 | 7 |
| $\delta$ | aus009a | usn010b | 75 | 30 | 6 |
| $\alpha$ | bkg001a | gsf007b | 88 | 23 | 10 |
| $\delta$ | bkg001a | gsf007b | 115 | 30 | 7 |
| $\alpha$ | bkg001a | iaa008c | 85 | 65 | 14 |
| $\delta$ | bkg001a | iaa008c | 110 | 74 | 8 |
| $\alpha$ | bkg001a | mao008a | 94 | 56 | 13 |
| $\delta$ | bkg001a | mao008a | 119 | 64 | 9 |
| $\alpha$ | bkg001a | opa008b | 92 | 20 | 10 |
| $\delta$ | bkg001a | opa008b | 120 | 33 | 7 |
| $\alpha$ | bkg001a | usn010b | 89 | 23 | 11 |
| $\delta$ | bkg001a | usn010b | 117 | 42 | 8 |
| $\alpha$ | gsf007b | iaa008c | 25 | 64 | 10 |
| $\delta$ | gsf007b | iaa008c | 30 | 73 | 7 |
| $\alpha$ | gsf007b | mao008a | 26 | 55 | 12 |
| $\delta$ | gsf007b | mao008a | 33 | 62 | 10 |
| $\alpha$ | gsf007b | opa008b | 23 | 21 | 10 |
| $\delta$ | gsf007b | opa008b | 28 | 32 | 8 |
| $\alpha$ | gsf007b | usn010b | 24 | 25 | 11 |
| $\delta$ | gsf007b | usn010b | 29 | 41 | 9 |
| $\alpha$ | iaa008c | mao008a | 59 | 47 | 15 |
| $\delta$ | iaa008c | mao008a | 68 | 53 | 10 |
| $\alpha$ | iaa008c | opa008b | 64 | 23 | 10 |
| $\delta$ | iaa008c | opa008b | 71 | 32 | 8 |
| $\alpha$ | iaa008c | usn010b | 64 | 26 | 10 |
| $\delta$ | iaa008c | usn010b | 74 | 43 | 8 |
| $\alpha$ | mao008a | opa008b | 52 | 23 | 12 |
| $\delta$ | mao008a | opa008b | 59 | 32 | 10 |
| $\alpha$ | mao008a | usn010b | 56 | 27 | 12 |
| $\delta$ | mao008a | usn010b | 64 | 45 | 10 |
| $\alpha$ | opa008b | usn010b | 21 | 24 | 10 |
| $\delta$ | opa008b | usn010b | 33 | 40 | 9 |

## 8.4 Conclusions

Comparison of individual contributed catalog solutions have showed that the individual catalogs are very close to each other. The systematic effects in general are at the level of 50 $\mu$as. The weighted post-fit residuals, evaluated after removing systematic effects for all common sources of pairs of catalogs are at the same level. That indicates good agreement between the different solutions. Considering that the individual catalogs were obtained with four independent software packages, and used slightly different data sets and analysis models, one could conclude that systematic effects and additional random errors in the newly generated celestial reference frame ICRF2 will not exceed $50 - 100\,\mu$as.