6 Data and Modeling Comparisons (DG, DSM)

One of the requirements for ICRF2 is that it should be consistent with the current realization of the International Terrestrial Reference Frame (ITRF) and EOP products. In practice, this means that it should be consistent with the VLBI contribution to ITRF2008, which is called VTRF2008 [Böckmann, Nothnagel, & Artz, 2009]. Thus, it was necessary for the ICRF2 solution to also solve for site positions, site velocities, and EOP. The level of agreement with VTRF2008 and EOP comparisons are discussed later in §10. The generation of ICRF2 is also required to use the best current state-of-the-art astronomical and geophysical models. Thus, the solution should use atmosphere gradients, the VMF1 troposphere mapping function model [Böhm, Werl, & Schuh, 2006], antenna thermal deformation, and the other standard VLBI models. Specifically, it should also use corrections for atmosphere pressure loading, even though they were not used for VTRF2008, since pressure loading is one of the state-of-the-art geophysical models that has become a standard VLBI analysis tool.

Some of the newer models have only recently become available in the analysis, such as the VMF1 model and the thermal deformation model. There was a desire to understand the effects of using different models, and to validate the newer models. Therefore, a number of model comparisons and tests were made. Tests were also made comparing subsets of the data, on the types of data, and on the data span. It was hoped that these tests and comparisons would help in determining the best data subset, the best analysis strategy, to identify and understand any systematic errors, and to help determine the noise floor. Some of these tests (decimation) are discussed later in §9. These tests were done at GSFC using the Calc/Solve analysis package. Most were made using preliminary catalog solutions, before the session and source lists were finalized. All the comparison tests except the VCS vs. non-VCS comparison used solutions without the 24 VCS sessions. In the discussions below of solution differences, the RA differences are always scaled by the cosine of the declination to give true arc lengths. A good summary of additional and complimentary comparisons using the OCCAM software can also be found in Tesmer [2007]. Their results generally agree with the results presented here.

6.1 Data Start Time Tests

The chronologically earlier VLBI data is known to be considerably noisier than later data. This has been due to many improvements over the past 30 years, such as: increased individual channel bandwidths, increased spanned bandwidths, improved electronics, new and more sensitive stations, larger networks, improved scheduling methods, and other factors. A question posed was whether to use data going back to the beginning of the Mark III era (August 1979), or to throw away the first few years of data. Alternate start times suggested were 1990 and 1993. One thought was, that although the earlier data is noisier, the formal errors are also larger and with proper weighting the earlier data should not degrade the reference frame. Three tests were made to study this issue, using data start times of Aug. 1979, Jan. 1990, and Jan. 1993.

When the start time is delayed from 1979 to 1990, there are some small differences in RA and declination for some sources, with some as large as $\sim$0.5 milli-arc-seconds (mas), but most much smaller. The formal uncertainties also increase slightly. The wrms differences between the ensemble of source positions estimated with and without the earlier data are 11 and 8 micro-arc-seconds (μas) in RA and declination, respectively. When the start time is delayed from 1979 to 1993, the differences are more dramatic. Large differences are seen for some sources, with a dozen

or so between 1 and 10 mas. The formal uncertainties for some sources also increase, some by ∼0.1 mas. Presumably, this is due to a greater emphasis on some sources in the earlier years. The wrms differences are 18 and 14 μas in RA and declination, respectively. From these comparisons, it was concluded that the earlier data, though noisier, will not degrade the reference frame, so it was used for ICRF2.

6.2 Data Type Comparisons

Another question was which types of sessions should be used. The earlier VLBI sessions were more concerned with plate tectonic and regional tectonic motion and less on Earth orientation and astrometry than the later sessions. Also, from 1982 until 1991 the Crustal Dynamics Project sponsored the Western U.S. and Alaska mobile VLBI campaigns. These used three small mobile VLBI systems (of 3, 5, and 9 meter diameter aperture), and the two smaller systems made repeated measurements at several dozen sites in California, Nevada, Arizona, Colorado, Alaska, and Canada to measure regional plate tectonics (see Clark et al. [1987] and Ma et al. [1990]). Data from the small mobile systems would not be expected to contribute to the celestial reference frame. However, most of these mobile sessions also used several large fixed antennas, such as OVRO130 (40 meter), Hatcreek (26 meter), Mojave12 (12 meter), Gilcreek (26 meter), and Westford (18.3 meter). These larger antennas would be expected to contribute to the celestial reference frame. A comparison was made of two solutions, one using only fixed station sessions (no mobile sessions) and one with mobile sessions added. When mobile sessions were added, very little difference in source positions were seen. The wrms differences are only 2 μas and the average differences are only 1 μas in both RA and declination. Only one difference was larger than 0.1 mas for a source observed in only a few sessions. There were no significant changes in formal errors and no significant rotation of the frame.

There was another class of sessions whose use was questionable. These were the small, regional sessions, like the JADE sessions, the Canadian regional sessions, most of the European mobile sessions, various "ties" sessions, and an assortment of special sessions not considered suitable for most VLBI analysis. Although these sessions were useful for their own purposes, they are made up of small or geometrically weak networks usually with only one large antenna and one or more small antennas. As such, they would not be expected to contribute much to the celestial reference frame. We made a comparison solution in which these sessions were added. When they were added in, the average position differences were not large, but some individual position differences were large, up to ∼1.6 mas, with 41 differences larger than 0.1 mas.

From these two comparison tests, it was decided to use most of the regular mobile sessions (with at least two well-separated fixed antennas) since they would add a considerable amount of data and could contribute to the reference frame, but not to use the smaller regional sessions, the ties sessions, or other special sessions.

6.3 Type of Solution: TRF vs. Baseline

There are two basic ways of treating the antenna positions in a solution. In a terrestrial reference frame (TRF) solution they are solved globally and the result is a set of antenna site positions and velocities at a specified epoch based on the entire observing history. In a baseline solution, site positions are treated as local (arc) parameters and separate positions are obtained for each session. In a TRF solution, one can apply no-net-rotation and no-net-translation constraints on the positions and

velocities of a set of core sites to align the TRF with an *a priori* reference frame. EOP are estimated for each session, except usually for 1-baseline sessions. Some sites show discontinuities due to earthquakes or mechanical movement of the antenna which must be modeled into the solution. In a baseline solution, no-net-translation constraints can be applied for the estimation of site coordinates for each experiment session. EOP is normally fixed to an *a priori* EOP series for a baseline solution.

For ICRF1 and its extensions, baseline solutions were made. However, for consistency with ITRF2008, ICRF2 must be generated as a TRF solution. Tests were made to see what effect this might have on the reference frame. Matching TRF and baseline solutions were made and compared. For both, the *a priori* TRF was VTRF2008 [Böckmann, Nothnagel, & Artz, 2009]. Comparison of these two solutions allows us to assess how much unmodeled site position noise in the TRF solution propagates to other parameter estimates, specifically the source position estimates. The two solutions show mostly only noise-like differences with wrms of 10-12 μas, and with no differences greater than around 0.6 mas. There are no declination-dependent systematic variations in the differences. Plots of the RA and Declination differences vs. Declination are shown in Figure 13. This comparison gives us confidence that the TRF requirement will not have any adverse effect on ICRF2.

6.4 Gradient Tests

The troposphere above VLBI sites is known to be azimuthally asymmetric, i.e. there are atmosphere gradients. In general, all stations have an average North-South gradient which increases towards the equator due to the pole-to-equator temperature gradient. East-West gradients also exist, but vary considerably over periods of days or less due to weather patterns. East-West gradients are expected to average out to near zero for most sites. If the refractive effects of atmospheric gradients are not accounted for, the radio source positions will be biased. This bias would be mainly seen in declination. For northern hemisphere stations, the N-S gradient will make lower declination sources appear higher in the sky, thus increasing their apparent declination. For southern hemisphere stations, the apparent declinations of higher declination sources will decrease. The northern hemisphere networks dominate though so that the maximum effect on declinations occurs south of the celestial equator. The end result is that, if gradients are not accounted for, the apparent declinations would increase by a maximum of $\sim$0.5 mas at $\sim -10^\circ$ declination.

The standard method of estimating gradients in program Solve has been to apply an *a priori* gradient model and solve for residual gradients. The *a priori* model of MacMillan & Ma [1997] was derived from a numerical weather model, and essentially gives a fixed N-S gradient for each site. The residuals can be solved for either by applying constraints or not. For a base solution, constraints of 0.5 mm and 2.0 mm/day on offsets and rates were imposed. Comparison tests were made in which: a) no *a priori* gradients were applied and no residual gradients were estimated; b) the *a priori* gradient model was applied, but no residuals were estimated; and c) no *a priori* model was applied, but total gradients were estimated.

As expected, a no gradients solution, compared to the standard gradients solution, shows a strong declination dependence—as was seen for the ICRF1 [Ma et al., 1997]. Without gradients, apparent declinations increase from the poles to a maximum of $\sim$0.5 mas at around -10° declination. If only mean *a priori* gradients are used, apparent declinations decrease by $\sim$0.05 mas for declinations south of around +10°. The *a priori* models thus appear to be statistically accurate at about the 10% level.

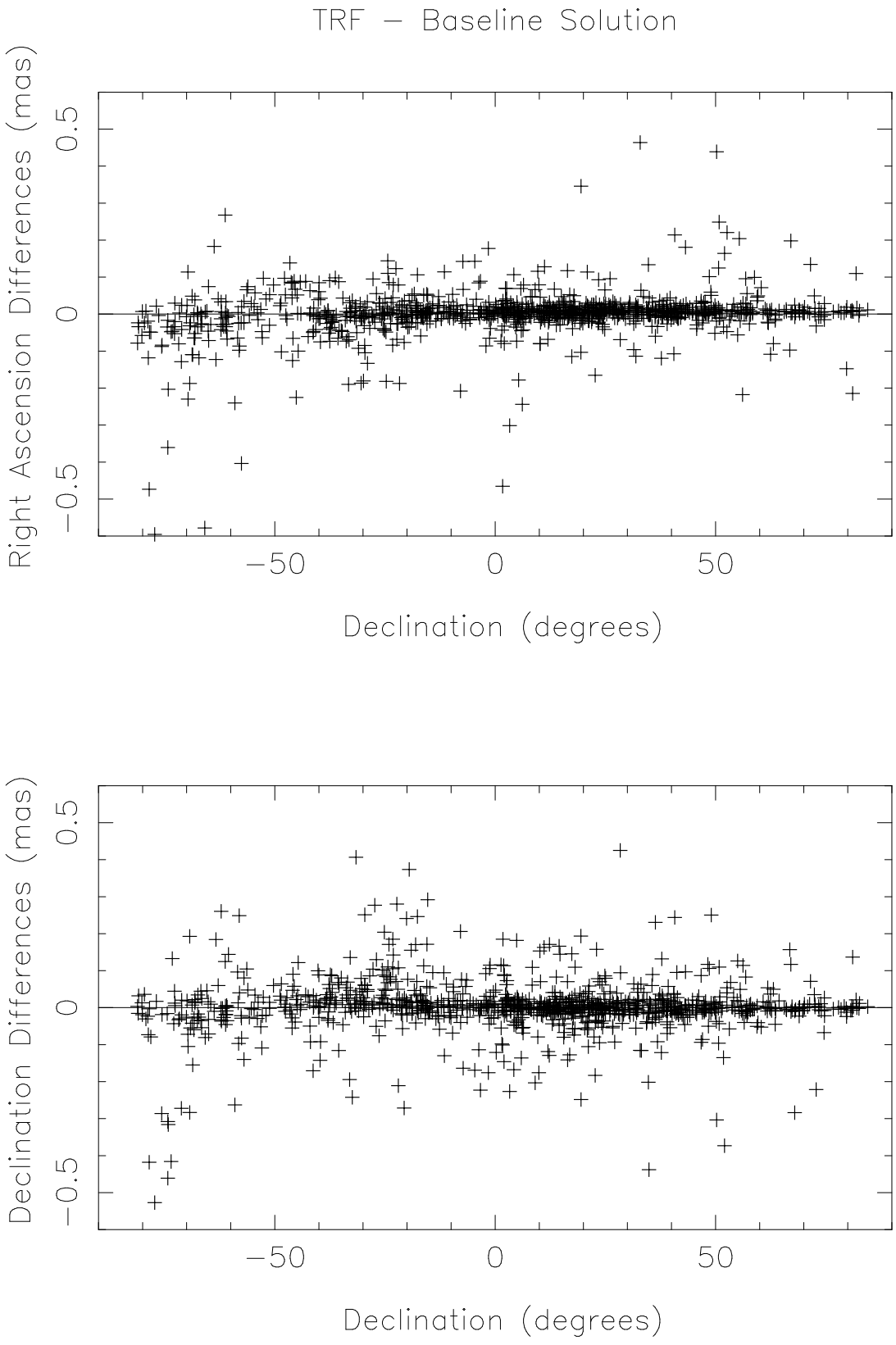

Figure 13: Differences between a TRF and a baseline solution. Sources with formal errors greater than 0.6 mas are not plotted.

A second method for estimating gradients is to estimate total gradients without the use of an *a priori* file. This is the method that was used for ICRF1 and its extensions, so a comparison of these two methods is very important. When a comparison was initially done, it was found that the constraints were too restrictive when used to estimate total gradients. Further tests were done in which the constraints were weakened four-fold and ten-fold. With these solutions, the agreement is very good, and all differences are less than ≈2.1 times their formal errors. Figure 14 shows the comparison plots for this case.

6.5 Pressure Loading Tests

Atmospheric pressure loading has become a standard VLBI analysis model over the past few years. Pressure loading corrections have been shown to improve VLBI baseline repeatability [Petrov & Boy, 2004], therefore it is desirable to use pressure loading for the ICRF2 solution. Pressure loading was *not* used for ITRF2008, at the request of the IERS, mainly because the other geodetic techniques were not using it. However, its use would not be expected to cause any adverse effects on the celestial or terrestrial reference frames or the EOP solution. Further, pressure loading is considered a current "state-of-the-art" geophysical model which thus should be used in the generation of ICRF2. Comparison solutions were made with pressure loading applied and not applied. Only small differences are seen in source positions, mostly less than 0.2 mas, and nothing systematic. Formal errors are unchanged. This test indicates that pressure loading corrections will have no adverse effect on the celestial reference frame.

6.6 Vienna Mapping Function vs. Niell Mapping Function

The VLBI contribution to ITRF2008 used the VMF1 mapping function [Böhm, Werl, & Schuh, 2006] for tropospheric delays, and it is considered the best current "state-of-the-art" model. Therefore, it should also be used for ICRF2. The previous standard was the Niell Mapping Function (NMF) [Niell, 1996]. We made comparison solutions using VMF1 and NMF. Catalog position differences are mostly small, but some as large as 0.8 mas are seen. There are only small, insignificant increases in uncertainties. VMF1 is derived from the ECMWF numerical weather model. Figure 15 shows the differences between using the two troposphere mapping functions, in units of formal errors. There are no differences greater than $0.9\,\sigma$.

6.7 VCS Test

The VLBA Calibrator Survey (VCS) sessions were VLBA only observing campaigns begun by Beasley et al. [2002] to obtain precise positions and snapshot maps of several thousand compact radio sources to increase the number of calibrator sources available for VLBI phase referencing. Five additional VCS campaigns were later carried out: Fomalont et al. [2003], Petrov et al. [2005], Petrov et al. [2006], Kovalev et al. [2007], and Petrov et al. [2008]. There were 24 successful VCS sessions. Use of these 24 sessions adds nearly 2200 additional sources to the catalog. Most of the VCS sources were scheduled for two scans (90 baseline observations) in only one session. A few sources were observed in two sessions. For many of the sources there are only a few good observations and their uncertainties are large. But also for many of them, there are many good observations, and their uncertainties are small. Therefore, it is desirable to include them in ICRF2, as long as doing so will not distort the frame. Comparisons were made with and without the 24 VCS sessions. Mostly

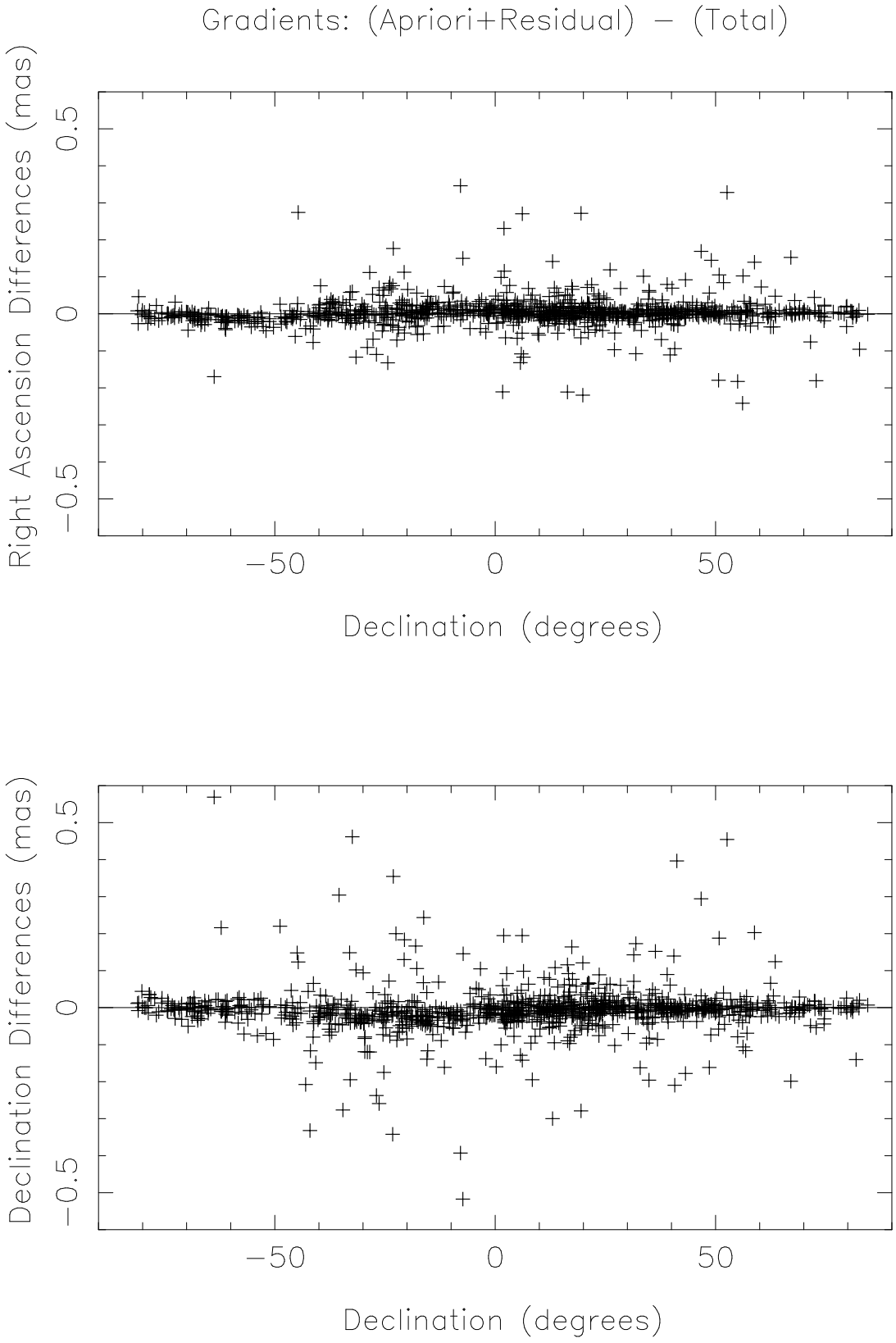

Figure 14: Differences between solving for gradients with an *a priori* mean gradient applied versus no mean gradient applied and using weak gradient constraints. Sources with formal errors greater than 0.6 mas are not plotted.

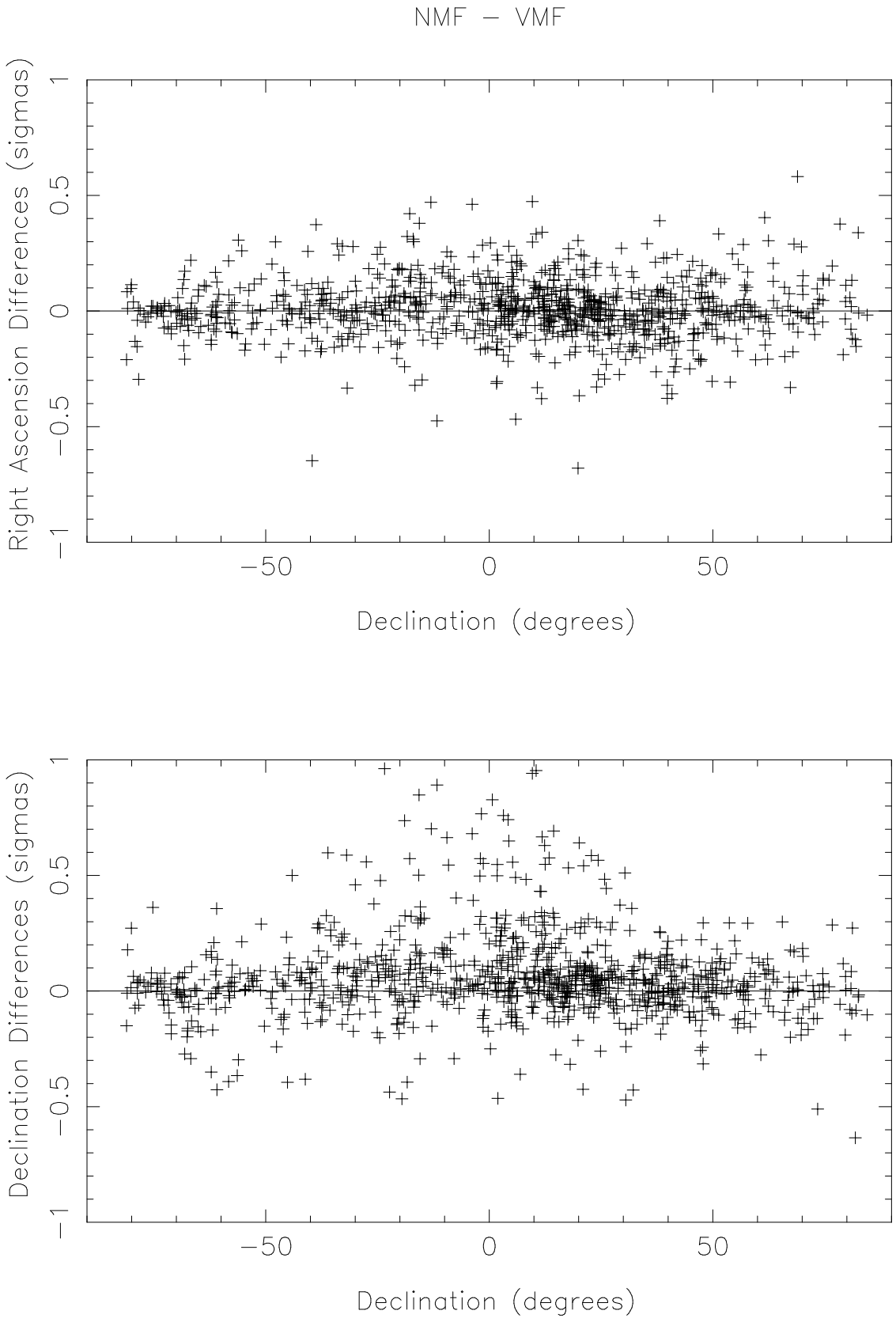

Figure 15: Differences between using the Niell Mapping Function (NMF) versus the Vienna Mapping Function (VMF1), in formal error units.

just small differences are seen. However, a few sparsely observed sources show large position changes (up to ∼200 mas) when the VCS sessions are added, due to a large increase in the number of observations, and presumably a better position. No systematic effects are seen. Figure 16 shows the position differences for cases where the number of observations (without VCS) is greater than four and the formal errors (non VCS) are less than 1 mas.

6.8 Thermal Deformation Test

The use of an antenna thermal deformation model was used for ITRF2008. Therefore it should also be used for ICRF2. The thermal deformation model described in Nothnagel [2008] accounts for the change in the position of the reference point of an antenna as a function of temperature relative to a specified reference temperature for each site. Specific information for each antenna (structural dimensions, expansion coefficients, reference temperature) are provided in Nothnagel [2008]. A comparison of source catalogs was made using thermal deformation and not using thermal deformation. Mostly small random differences are seen, up to ∼0.1 mas. Formal uncertainties are virtually unchanged. Figure 17 shows the differences, in formal error units.

6.9 Summary of Data and Model Comparisons

Table 2 summarizes the results of the various data and model comparisons. We present the weighted means of the differences and their wrms in Right Ascension and declination, as well as the overall rotation angles between the pairs of solutions. It will be seen that any uncertainties due to the data or model options are all smaller than the estimates that will be presented later for the ICRF2 noise floor and axes stability.

Table 2: Summary of Data and Model Comparisons

Data/Model Comparison	$\Delta\alpha\cos\delta$		$\Delta\delta$		Rotation Angles		
	mean (μas)	wrms (μas)	mean (μas)	wrms (μas)	X (μas)	Y (μas)	Z (μas)
Start Time: 1979 vs. 1990	1	8	1	11	0	2	1
Start Time: 1979 vs. 1993	0	14	0	18	-1	5	4
Session Type: Fixed vs. Fixed+Mobile	-1	2	-1	2	0	0	-1
Session Type: Fixed vs. Fixed+Mobile+Regionals	0	5	-2	5	2	-1	-3
TRF vs. Baseline	-1	10	0	12	2	2	2
Gradients: *a priori* vs. No *a priori*	0	7	6	12	8	5	3
Pressure Loading: On vs. Off	0	2	0	3	2	1	0
VMF1 vs. NMF	-1	3	-3	5	-1	2	-1
VCS vs. No VCS	2	17	1	18	-7	1	1
Thermal Deformation: On vs. Off	0	0	0	1	0	0	0

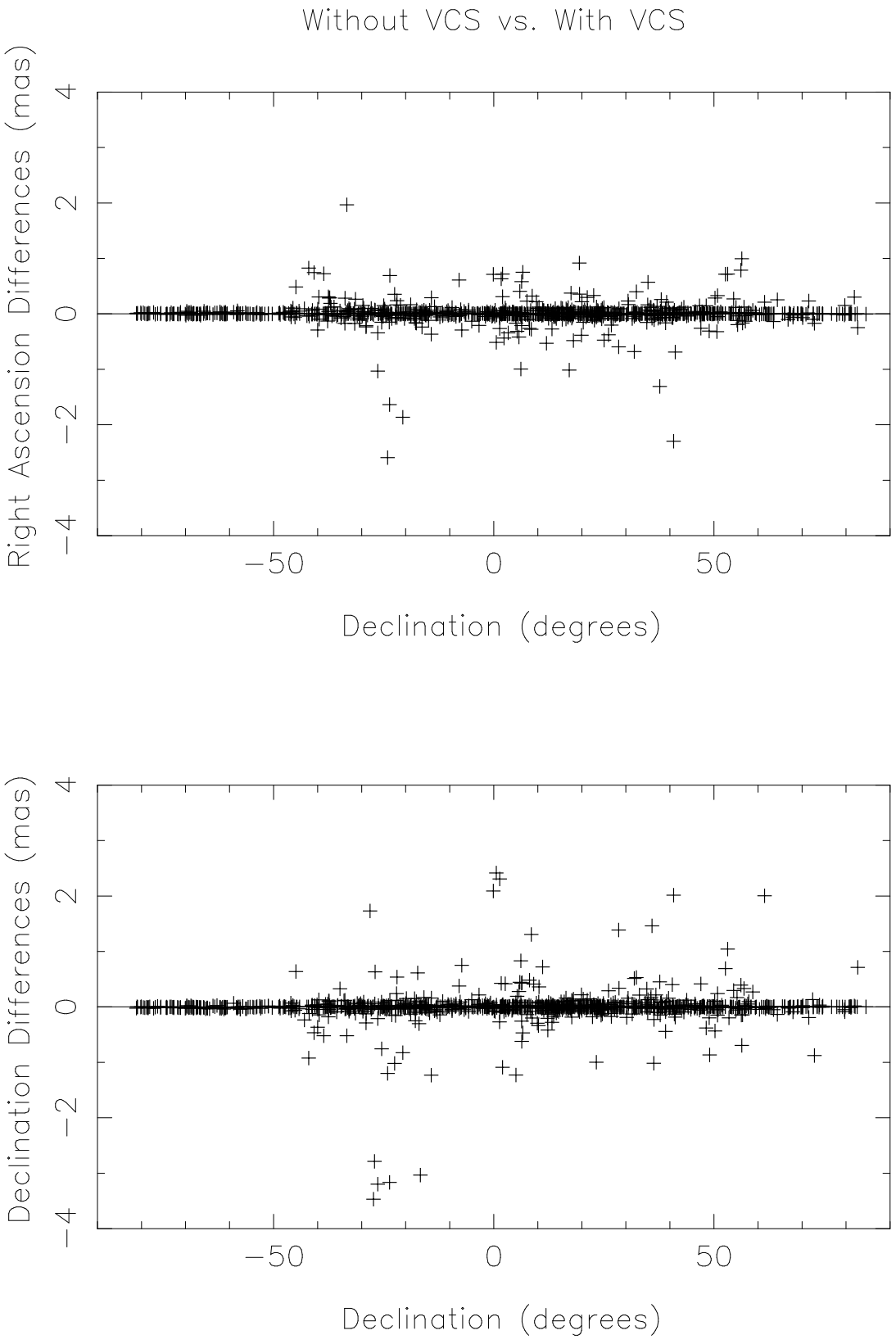

Figure 16: Solutions with and without the VCS sessions. Sources with fewer than four observations or formal errors greater than 4 mas are not plotted.

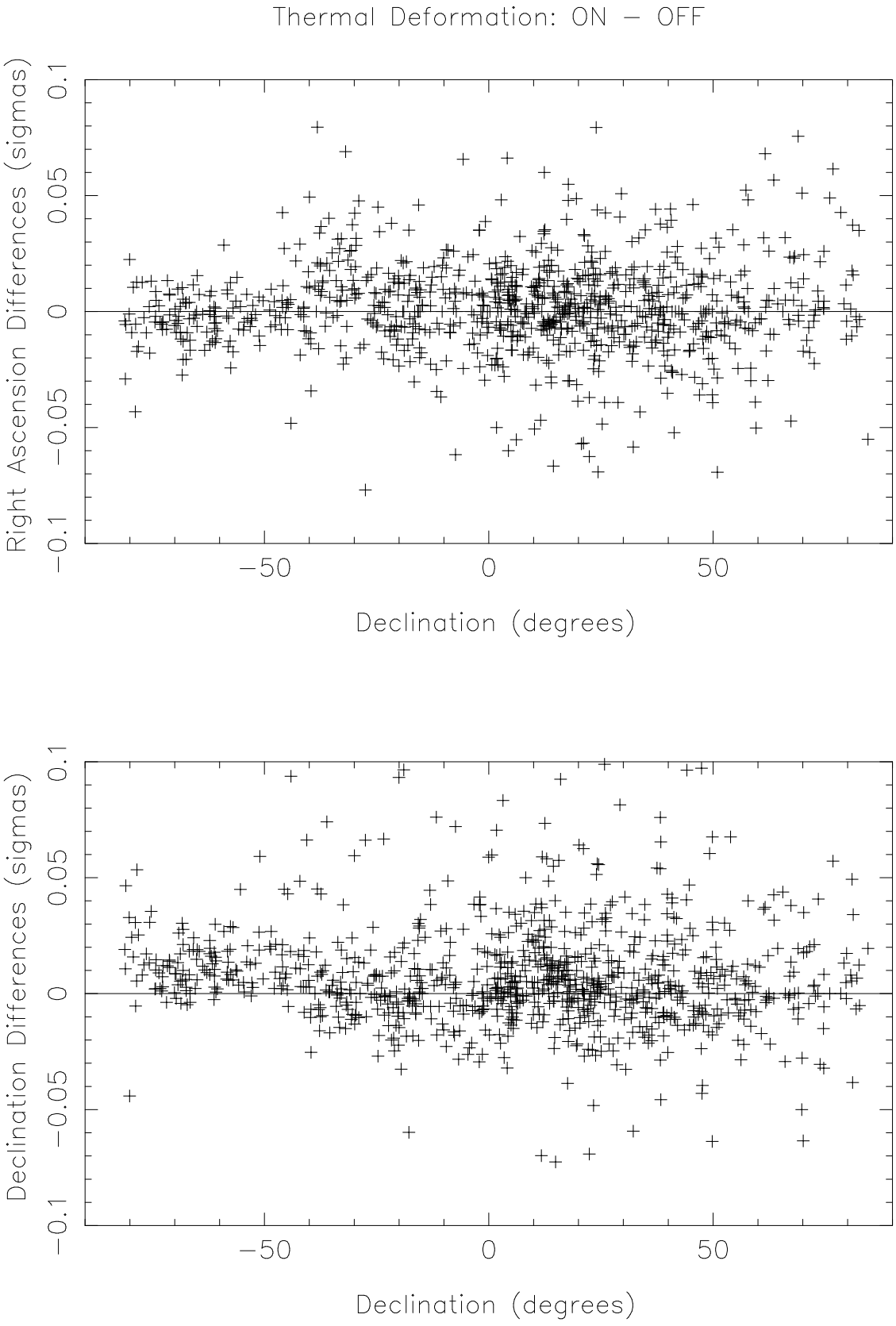

Figure 17: Differences between applying antenna thermal deformation and not applying antenna thermal deformation, in formal error units.