Opacity Correction for High Frequency VLBI Observations

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Introduction

High frequency VLBI observations (in this document 22 GHz and higher) suffer from considerable atmospheric effects not properly addressed by standard VLBI calibration methods. These effects affect both the phases — basically making the coherence time variable with time — and amplitudes — making the amplitude gains of stations strong functions of elevation and time. The atmospheric effects on phases are corrected to a high degree by standard self calibration, unless the coherence time is shortened enough to make the source undetectable. However, the standard amplitude calibration methods developed mostly for lower frequency observations usually neglect atmospheric effects and only make a gain correction for the gravitational deformation of the dish. This leads to *a priori* calibration errors often exceeding 50 percent at mm-frequencies and considerably reducing the attainable dynamic range in maps. There is a provision for opacity correction in AIPS: the task CLCOR can be used to compensate for opacity as a function of elevation, thus assuming a constant zenith opacity during the experiment (which must be separately derived for all the stations from the system temperature measurements). Unfortunately, unchanging atmosphere is not a reasonable assumption for most experiments more than a few hours in duration. Weather phenomena such as rain or fast moving wet clouds can substantially change the amplitude gain of a station over time scales of a few minutes and corrupt the amplitudes of otherwise perfectly valid visibility points.

Until now the few investigators using high frequency VLBI data have devised their own ways of dealing with these problems or have left the correction of amplitudes to self calibration (a dangerous approach if one does not have many stations and a fair amount of amplitude closure in the data set). With the VLBA coming on line with routine mm-observations and envisioned high degree of transparency to the end user, a better approach to amplitude calibration is clearly needed. Fortunately, this is made possible by the good system temperature and weather monitoring implemented for the array. In this memorandum I describe a simple idea for using this monitor data to estimate the atmospheric attenuation as a function of time (rather than elevation) to correct the visibility amplitudes, how it worked with real data, and what kinds of problems were encountered. I also describe a C-program written to perform this correction and give some suggestions regarding a possible approach to routine amplitude calibration scheme for the VLBA (and global VLBI).

System temperature and atmospheric attenuation

In this memo I will use the radio engineering term atmospheric attenuation as the factor by which the received flux density from the source is reduced by the atmosphere and (zenith) opacity as the optical depth of the atmosphere at zenith (or, equivalently, zenith attenuation in Nepers).

For the purposes of this discussion the total system temperature towards the source at a given station can be regarded as the sum of three terms: the sky brightness temperature, the receiver (system) temperature, and spill-over from the ground (with the exception of some maser sources the source contribution is usually so small it can be ignored):

$$T_{sys}(t) = T_{sky}(t) + T_{rec} + T_{spill}(elev)$$

Of these the receiver temperature will be considered constant during the observation including thus all terms independent of source direction. The spill-over is assumed to be only a function of elevation and the same for all stations and frequency bands. This assumption is clearly incorrect, but since we are dealing with a small effect difficult to quantify precisely, it is used as an approximation until better information is available. The sky brightness temperature (or sky temperature for short) carries information on the atmospheric attenuation L *along the line of sight* according to the simple equation

$$T_{sky} = T_{atm}(1 - 1/L)$$

T_{atm} is the effective physical temperature of the atmosphere, i.e. the average temperature along the line of sight weighted by the absorption coefficient. Most of the attenuation occurs low in the atmosphere and T_{atm} can thus be estimated with reasonable accuracy from the ground air temperature. Thus, if T_{sky} is known, the attenuation L can be computed. Note that this formula does not make any approximations of e.g. the air mass and works equally well for all elevations or zenith opacities as long as T_{atm} is known. T_{atm} is independent of elevation if the atmospheric temperature is only a function of altitude, i.e. the atmosphere is horizontally stratified in the vicinity of the station. The VLBA records the system temperature at least every two minutes (other stations typically once every scan) leaving only the problem of knowing and subtracting T_{rec} and T_{spill}. T_{rec} can be measured using hot and cold loads or estimated by fitting an elevation dependent model of sky temperature, and should remain essentially constant if the receiver is working properly. T_{spill} is more difficult to obtain, but calibration observations made by Vivek Dhawan and Craig Walker indicate that it assumes significant values above the contribution at zenith (on the order of 10 K) only at low elevations (< 20 degrees) and a simple functional form for it should be adequate.

The standard way of calibrating the visibility amplitudes in AIPS is to use the task ANCAL to read system temperatures and antenna gains / antenna temperatures from a calibration file, and to calibrate a CL table. Antenna temperature measurements are in principle a superior way of calibrating visibility amplitudes since they include atmospheric as well as other effects (such as pointing) influencing the instantaneous gain of a given antenna. In practice, however, they suffer from many problems: only the largest dishes have the sensitivity to measure T_{ant} for a typical VLBI source, the measurements have relatively large errors, and they can only be made infrequently (usually once every scan). This leaves the a priori gain information together with the system temperatures as the principal mode of calibration. These are used by ANCAL to compute the gain calibration factors GF for the antenna j as follows:

$$GF_j = BDEFAULT \cdot \frac{T_{sys,j}}{DPFU_j \cdot POLY_j}$$

where $BDEFAULT$ is the correlator b-factor, $DPFU$ the antenna peak gain (Degrees Per Flux Unit), and $POLY$ the normalized gain curve. Even though this calibration makes use of the measured system temperatures, it does not correct for gain errors caused by the atmosphere. On the other hand, it suggests a very simple way of introducing an attenuation correction derived from the system temperatures into ANCAL. If the T_{sys} values read by ANCAL are multiplied by the estimate of instantaneous attenuation L, the required correction for telescope gains and visibility amplitudes is achieved. This does not require any modification of the AIPS software and allowed me to do experimentation with this calibration scheme using real VLBI data sets.

A procedure for attenuation correction

If the receiver temperatures of the stations were known, the estimation and correction of the attenuation would be straightforward. Even though observatories have some idea of what these values for their receivers are, they do not usually include this information in their calibration sheets. Also it is not clear how stable the receiver temperatures are over periods of weeks or months, i.e. how well the receivers are maintained in their optimal operating condition. The receiver temperatures of the VLBA receivers have been measured before installation, but these values are not representative of the values in the antenna environment due to e.g. additional losses in the reflector surfaces or moisture on the feed.

Fortunately, the receiver temperature can be estimated from the system temperature values, if these cover a sufficient elevation range. This can be done by fitting and subtracting elevation dependent models for the sky temperature and spill-over from T_{sys}. A simple model for T_{sky} adopted here is based on the secant law for air mass and it has only one free parameter, zenith opacity τ_0:

$$T_{sky}(\tau_0, elev) = T_{atm} \cdot \{1 - \exp[-\tau_0 / \sin(elev)]\}$$

The easiest way to estimate the atmospheric temperature T_{atm} is to use the ground air temperature measurements. It has been found (Elgered 1981) that the highest daily ground temperature has a relatively high correlation with T_{atm}, which is relatively independent from the diurnal temperature variations on the surface. For this analysis two schemes were tried:

$$T_{atm} =< T_{ground} > -15K$$

where $< T_{ground} >$ is an average over the experiment, and (Elgered 1981)

$$T_{atm} = \max\{T_{ground}\} \cdot 0.652 + 84.6K$$

These gave values differing only by a few degrees and leading to negligible differences in the derived receiver temperatures. It might be possible to employ the VLBA weather monitor data (or data produced by the MkIII field system at other stations) in a more sophisticated way together with simple atmospheric models. However, the attainable improvement in the T_{rec} solution accuracy is likely to be minor.

For spill-over a simple empirical model based on the analysis of VLBA calibration observations by Vivek Dhawan and Craig Walker is used. The spill-over can be thought of as the sum of three effects: 1) radiation scattered to the feed by the subreflector quadrupod structure; 2) at low elevations the feed horn sees the warm ground directly past the subreflector; 3) at all elevations radiation from the ground passing the edge of the main reflector is reflected to the feed by the subreflector. The behavior of the possibly large first term is difficult to predict heuristically. The last two terms have opposite elevation dependencies and they tend to cancel each other. However, the second term dominates over the third and makes the spill-over peak strongly at low elevations (and a strong function of the local horizon; this is neglected here, however). Fortunately, the sky temperature is also highest at low elevations thus making the fractional error due to uncertainty in the spill-over smaller. The model used is a linear interpolation from the table below (a constant term is subtracted to make T_{spill} zero at zenith).

$elev\,[deg]$	2	15	20	25	30	40	50	70
$T_{spill}\,[K]$	12	11	9	6.5	5	2	1	0

An estimate of the receiver temperature (and the zenith opacity as a side product) can now be obtained by least squares minimization of the residuals δ_i with respect to τ_0 and T_{rec}:

$$\delta_i = T_{sys}(elev_i) - T_{sky}(\tau_0, elev_i) - T_{rec} - T_{spill}(elev_i)$$

Since the secant law for air mass breaks down at low elevations (< 15 degrees) it is advisable to exclude those points from the fit. If the zenith opacity remains reasonably constant during the time range used for the fit, fairly accurate values for T_{rec} and τ_0 can be obtained. Unfortunately, at high frequencies this is not usually the case, which in single source experiments often shows as bimodal $T_{sys}(elev)$ curve. Also, short period disturbances like rain showers show as deviating or 'bad' points in T_{sys} vs. elevation. This makes the least squares solution more difficult as these deviating points (representing differing zenith opacities) must be down-weighted in order to get a useful estimate of T_{rec}.

The least-squares fit procedure used here is based on the Levenberg-Marquardt method (LMM; see, for example, Press 1988), which is an iterative algorithm combining the ideas of inverse-Hessian and the deepest descent methods. Every data point can be assigned an estimate of its standard deviation and normally these are kept constant during a set of iterations yielding the final solution. To introduce a weighting scheme multiple sets of iterations are performed and the standard deviations updated between these 'major cycles'. This avoids modifying the standard deviations between single LMM cycles, which easily leads to an unstable algorithm. The standard deviation estimate σ_i for the data point i deviating from the present model by δ_i (as defined above) is updated as follows:

$$\sigma_i = (\gamma \frac{{\delta_i}^2}{\Sigma^2} + 1)\Sigma$$

where Σ is a fixed estimate for the standard deviation of T_{sys} measurements, and γ governs how much weight is given to the distance of the data point i from the present model in the update. γ is increased by a constant amount after each major cycle as the model improves. It is preferable to start with initial guesses giving *too low* model sky temperature, since this way the algorithm tends to 'find' (approaching from 'below') a set of points with lower system temperatures usually corresponding better weather conditions. It is also possible to give higher weights to points with negative δ, but this inevitably leads to a bias in the fit.

To implement and test the described procedure I wrote a C-program OPACOR, which is able to do the following: it can read either an ANCAL calibration file or a VLBA calibration file produced by the TSM program, estimate the effective atmospheric temperature on the basis of VLBA weather monitor data, solve for the receiver temperatures by making the fit described above, compute the atmospheric attenuation for all the stations as a function of time, modify the system temperatures to compensate for the attenuation, and finally produce a new calibration file for ANCAL. The program also produces plots showing the system temperatures and estimated sky temperatures together with the fits and the computed attenuations. The use of the program is described later in this memo.

Results and problems

Performance of the described procedure was investigated using a few data sets at 13 and 7 mm. One of these sets — 13 mm Mk2 observations of 3C 345 in June 92 using 14 stations — turned out to be excellent for this purpose. The data quality was exceptionally good on most baselines due to the strength of the source ($\sim$ 13 Jy at the time of observation) and fairly new sensitive receivers at most sites, allowing the amplitude effects to be assessed precisely. Moreover, the source turned out to be practically unresolved on short baselines enabling reliable self-calibration of the antenna gains. These could then be compared with the corrections derived independently by OPACOR. All the results described below are related to this single source data set.

Figures 1 to 4 are plots produced by OPACOR. They show four subplots per station (three stations per page): the two at left show the fits as a function of airmass and elevation, and the two at right show T_{sys} and estimated attenuation L as a function of time. Note how the program has rejected 'bad' points *from the fit* for e.g. Bologna and Brewster, which experienced periods of high attenuation (thick fog and rain, respectively) lasting 3–5 hours. Naturally these points were still used for the attenuation estimate. VLA shows a fairly typical bifurcated $T_{sys}(elev)$ curve indicating a change in opacity near the time when the source culminated. North Liberty had a warm receiver cooling down until about 3 UT showing high and gradually decreasing system temperatures. In these cases the program selected a branch having more consistent or physical T_{sys} values. It is obvious that an ordinary least squares fit somewhere 'in between' would have given a useless value for the receiver temperature. However, the attenuation estimate for North Liberty during the receiver cool down period is mislead (much too large) by the changing receiver temperature. Actually, the program spontaneously flagged T_{sys} points taken before 0 UT, which are shown in the attenuation plot at unity amplitude. Even though the program has some ability to make a 'smart' fit, there is a pitfall in making long time span fits: if the opacity changes smoothly and continuously, the fit yields wrong estimates, even though it may look 'good'.

Figures 5 and 6 show amplitude gain solutions for all the stations made by AIPS task CALIB using a data set calibrated the usual way (uncorrected T_{sys} values and a priori gain curves), a clean component model for the source derived by hybrid mapping the source, and only short (continental) baselines ($< 250 M\lambda$). Bonn and NRAO were calibrated using antenna temperatures and consequently no attenuation correction was applied to these stations. Note that especially NRAO is still affected by gain problems most probably due to pointing problems together with noisy and sparsely spaced T_{ant} measurements. If all the gain variations were caused by the atmosphere, the CALIB solutions should be close to the voltage gain corrections given by OPACOR (square root of attenuation; shown as a dotted line on the attenuation plots). Overall, there seems to be a relatively good agreement, which is promising since these two sets of values were derived using completely independent methods and data (correlation coefficients and T_{sys} measurements).

Figures 7 and 8 again show amplitude solutions by CALIB, but this time after the opacity correction (no gain correction based on crossing point analysis applied; see below). Values exceeding unity imply that the gain correction was not large enough whereas values less than unity indicate overcorrection. Note how e.g. the gains of Bologna and Brewster (which were known to be affected by weather) were changed by the correction. Many stations still show fairly large residual gain errors, especially Onsala and VLA, probably due to pointing, deviations from the a priori gain curve, loss of coherence, or other technical reasons. Pietown and Fort Davis appear undercorrected at low source elevations but overcorrected elsewhere. This cannot be explained by wrong T_{rec} estimates alone. It is likely that this effect is at least partly due to non-flat gain curves of these antennas at 1.3 cm.

There appear to be small changes even in the gain solutions for uncorrected stations (Bonn and NRAO) indicating that the solutions made by CALIB were not ideal (probably due to the fact that only a few stations could be used for these particular solutions). No correction was applied to Crimea due to unreliable solution for the receiver temperature. The overcorrection for North Liberty during the receiver cooling down period is clearly visible. Owens Valley shows a strange stepwise gain *increase* lasting about 2 hours and not reflected in the T_{sys} data implying an instrumental effect.

The case of Brewster is shown more clearly in Figure 9, which shows the amplitudes on two Brewster baselines before and after the atmospheric correction. The most significant change is in the overall level of visibility amplitudes, which were brought close to the single dish flux density $\sim$ 13 Jy. The amplitudes during the period of heaviest rain were considerably flattened, but the opacities at low source elevations were clearly undercorrected. Again, this may indicate a non-flat gain curve - not necessarily opacity undercorrection. It is interesting to note that weather phenomena causing attenuations on the order of three do not necessarily introduce noticeable coherence losses (the noise level was clearly increased, though).

Currently two difficulties affect this method of amplitude calibration. The system temperature values for VLBA antennas are not necessarily calibrated correctly due to uncertainty in the noise diode (calibration) temperature, T_{cal}. This is not a problem in the conventional amplitude calibration, since the noise diode is known in Janskies ($T_{cal}/DPFU$) from astronomical observations. The fact that the $DPFU$ values at e.g. 13 mm vary by a factor of about two strongly indicates that the T_{cal} values of at least some stations must be wrong by a large margin. As the system temperatures are directly proportional to the assumed value of T_{cal}, an error in it causes the derived receiver and sky temperatures, and consequently the attenuation, to go wrong in a non-linear fashion. The only way to avoid this is to actually measure the T_{cal} values in Kelvins using hot/cold load techniques. An attempt to scale the T_{sys} values assuming equal gains for all sites did not produce acceptable results indicating that there are significant differences in the antenna efficiencies. In the final calibration only Fort Davis' extremely low T_{sys} values were scaled by a factor of 1.39 to bring the gain to a 'nominal' value of 0.889 K/Jy (corresponding to an aperture efficiency of 50 percent).

The T_{cal} and T_{rec} values for the VLBA 13 and 7 mm bands are being measured using hot and cold loads at this writing. The first results indicate that on the 13 mm band there is an excess noise temperature at zenith of 10–20 degrees above the actual receiver temperature. This cannot be accounted for by spill-over and cosmic background alone, which add up to maybe 10 degrees at most. The rest is presumably produced by losses in the main and subreflectors (paint etc.). In OPACOR this excess is completely absorbed in the receiver temperature so that the sum of receiver and excess temperatures (or equivalently, the difference between system and sky temperature at zenith) derived from the hot/cold load measurements should be directly comparable. Incidentally, the actual T_{cal} scale error for Fort Davis turned out to be 1.36 according to hot/cold load calibration.

Another difficulty is the usually unknown amount of opacity already included in the a priori gain information. The VLBA gains should be free from opacity effects, but this is usually not the case with the other antennas. The calibration information supplied by them is in most cases insufficient to even judge whether an attempt was made to remove atmospheric effects. Since OPACOR applies full opacity correction to all stations, this leads to relative gain errors and decreased dynamic range in mapping (naturally this would be the case even without the correction). One way to correct for this is to use redundant visibilities at crossing points on the uv-plane. Since there is no provision for this in AIPS I used the Caltech package program

UVCROSS to analyze the relative gain errors after applying the opacity correction. This yielded corrections consistent with the self-calibration for most stations, and is clearly an advisable step after OPACOR.

Even though some antennas appear to show fairly large residual errors after the application of the correction due to reasons probably not related to attenuation, the calibration is clearly improved by OPACOR and this approach seems worth pursuing further. As more experience on operating the VLBA is gained the relative significance of non-atmospheric calibration errors (such as pointing errors) is likely to become smaller possibly enabling amplitude calibration to within a few percent even at the highest array frequencies. One would also expect that the understanding of spill-over and receiver temperatures improves with time making this calibration method more accurate.

Suggestions

The hot/cold load measurements of calibration and receiver temperatures, even though difficult, should be repeated regularly to maintain the accuracy of absolute calibration. If this turns out to be too labor-intensive, it may be possible to use the Moon for this calibration. In addition to enabling the described opacity correction method to work better this information would also enable accurate derivation of zenith opacities from tipping curve measurements. Good knowledge of the receiver temperatures could do away with the need of using fits spanning complete experiments, which tend to be unreliable in changing weather conditions. It is not clear how stable the receiver temperatures are over periods of weeks or months; the data sets processed so far hint at the possibility of changes more than ten degrees over periods of few months. If the receiver temperatures turn out to be unstable, they can be reliably derived from tipping curve measurements, which cover a short enough time span ($\sim$ 10 minutes) for the opacity to remain essentially constant. These measurements should be scheduled at appropriately short intervals to maintain a continuous record of the receiver temperatures for calibration purposes.

There are also some doubts as to the stability of the calibration temperatures generated by the noise diodes. As this problem would also affect the *conventional* a priori amplitude calibration, it should be investigated thoroughly (with regular hot/cold load measurements, for example) and the noise diodes possibly replaced by the presumably more stable phase calibration signal as the primary means of T_{sys} measurement. On the other hand, it may be sufficient to simply replace the present voltage-regulated noise diode power sources with current-regulated ones.

Better station specific estimates for the spill-over term could be derived from a simple analysis of the known local site horizons and feed horn radiation patterns. Regularly scheduled tipping curves could also help determine the correct spill-over models, since errors in them show as inconsistencies in receiver temperatures derived during periods of different zenith opacities. It may be possible to use observations of the Moon to measure the spill-over directly.

The calibration information produced by the VLBA should include an estimate of attenuation based on the system temperatures, the weather data, the spill-over model, and the continuous history of receiver temperatures. This estimate would then be used together with the gains and system temperatures by the software performing the a priori amplitude calibration. The same information should also be provided by the non-VLBA stations in similar format and time resolution.

Finally, I suggest that an uv-plane crossing point analysis of the station amplitude gains be added to AIPS for reasons explained elsewhere in this memo.

Using OPACOR

The program reads an ANCAL calibration file (input file) and produces a file in the same format but with the system temperatures modified to account for attenuation (output file). It can also read a VLBA calibration file produced by the program TSM and append the extracted T_{sys} information to the output file. It is preferable to read the VLBA cal file directly, as it contains additional information about weather, source changes etc., which is used by the program. The behavior of OPACOR is controlled by control parameters in the input file; all of these will be described below. The input file looks something like:

```
source='3c345'
flux=13.16
year=1992 !  Control parameter for OPACOR
calfile = gz8b/gz8bcal.vlba
bdefault=1.0
nostations=bonn,nrao
avgchan
zalimit=80
/ !  This slash marks the end of the control card.
tsys onsa tatm=2.0 / !  Some parameters can be placed on the tsys line.
.
.
/
gain onsa ..  /
```

Thus, except for extra parameters in the control card, this is a standard ANCAL input file. Some additional rules must be observed: only one parameter is allowed per line, no expression evaluation is performed, and the '/' delimiter of the control card may not be on a line containing other slashes. The parameters cannot be abbreviated and no quotes should be used in the OPACOR control parameters. Case, spaces, or the order of the parameters have no effect. The tsys card may only contain one T_{sys} entry on each line. Everything appearing after an exclamation mark is regarded as a comment. The parameters used by ANCAL (or not recognized by OPACOR) as well as gain and tant cards will be copied to the output file. The control parameters and their meanings are as follows:

`year` — The year of observation. This is needed for accurate computation of source elevations. *Must be given.*

`source` — The source name. This is a standard ANCAL parameter (quotes around the source name allowed) used by OPACOR only for stations in the *input* file (only one source allowed). If the experiment has multiple sources, a VLBA calibration file must be used.

`calfile` — The VLBA calibration file. If only the VLBA was used, the input file might only contain the control card. OPACOR does not automatically write gain information for the VLBA to the output file, but copies it from the input file, if present. A path may be given.

`srcfile` — OPACOR needs source coordinates to compute elevations and looks for them in the file /u/cwalker/sched/sources.obs. If the source is not found there, the program uses a secondary catalog given by `srcfile`. A path may be given. For information, the station coordinates are read from /u/cwalker/sched/stations.dat.

`stations` — Process only the stations listed. Gain, tsys and tant cards for other stations are just copied to the output file.
Example: `stations=pt,la`

`nostations` — The opposite of `stations`. This is useful if a station has a tant card and the tsys card should be left intact. NOTE: tsys cards with the keyword `src/sys` will not be processed.

`timerange` — Specifies the T_{sys} time range to read, process, and write. Examples:

```
timerange=164-12 to 164-18 !  Day of year 164:  UT 12-18
timerange=164.5 to 164.75 !  As above
timerange=to 170-6 !  From the beginning to 170-6
timerange=170-6 to !  From 170-6 to the end
```

`slewtime` — OPACOR rejects T_{sys} measurements made less than `slewtime` (in minutes) after a source change. Default: 2.0.

`polarization` — Selects the polarization (lcp or rcp) in dual polarization VLBA observations. Only channels of the given polarization are processed and written to the output file.

`avgchan` — If given, all the T_{sys} channels (of given polarization) in the VLBA calibration file are averaged and the output file will have only one channel. This happens always when there are more than eight channels. The fit and the attenuation computation always use an average over the channels.

`zalimit` — Only T_{sys} points with smaller zenith angles (degrees) are used in the T_{rec} fit. Default: 75.0.

`tatm` — List of effective physical atmospheric temperatures in Celsius for the stations. These *must be given* for non-VLBA stations and can also be given for the VLBA sites, in which case the temperatures are not read from the cal file weather section. `tatm` can also be given in the tsys card. NOTE: the temperatures are used as given, i.e. ground air temperatures should not be specified as they are usually too high.
Example: `tatm=onsa,0,kp,10,vlba_br,-5`

`tatmavg,tatmft,tatmoff` — These govern how the atmospheric temperatures are computed from the ground temperature values in the VLBA cal file weather section. The model is: $T_{atm} = \mathtt{tatmft} \cdot < T_{ground} > + \mathtt{tatmoff}$, where $<>$ is average over `tatmavg` days. If `tatmavg` < 0, the maximum temperature is used instead of average.
Defaults: `tatmavg=0.5, tatmft=1.0, tatmoff=-15.0`.

`weatherfile` — A separate weather data file using the TSM weather section format can also be used for the VLBA stations. The weather information should cover at least the duration of the experiment. If `tatmavg` < 0 is used,

	the weather data should preferably span one full day. If `weatherfile` is not specified, OPACOR tries to find a weather section in the VLBA calibration file.
`ft2`	List of T_{sys} scaling factors used *only* for the fit and computation of attenuation to correct for T_{cal} scale errors. I.e. they are not applied to the output T_{sys} values (otherwise the gains should be modified accordingly). Default: 1.0. Example: `ft2=vlba_fd,1.39,kp,1.1`
`guess`	List of initial guesses for T_{rec} and τ_0. In some cases the fitting algorithm has difficulties in judging which points to exclude from the fit and can be helped by choosing appropriate guesses. If only T_{rec} is given, the program assumes it to be known and uses the value directly to compute the attenuation, i.e. no solution for T_{rec} is made (see also `tau0`). Example: `guess=la,100,0.12,pt,95,nl,80,0.08 ! No fit for PT`
`trec,tau0`	Global initial guesses. Their values are overridden by station-specific guesses. If one wants to fix T_{rec} (not solve for it, see `guess`), `tau0` must not be specified.
`nospill`	If given, no spill-over correction is applied.
`nofit`	If given, disables the fit algorithm. This is useful for finding better initial guesses for stubborn cases as the 'fit' based on the initial guesses is still shown on the plots. One might want to specify the troublemaker using the `stations` parameter.

`plotdev`	PGPLOT plotting device. Examples:
	`plotdev=opacor.ps/vps ! plot file / device (this is the default)`
	`plotdev=/xview ! plots on the screen`
	For more info, consult the PGPLOT manual.

`nplot`	Number of stations on each plotted page (each station has four subplots). `nplot=0`: no plot generated. Default: 3.
`project`	Project code. If given, it is shown on the plots.

The tsys cards may also contain some station specific parameters:

`ft`	If given, the T_{sys} values are multiplied by this factor. This is exactly like the ANCAL `ft` parameter.
`ft2`	Scaling factor for the T_{sys} values. See parameter `ft2` above.
`tatm`	Atmospheric temperature in Celsius.
`tau0,trec`	Initial guesses for the receiver temperature and the zenith opacity.

These values are overridden by values given in corresponding control card parameters. Note that the ANCAL parameter `timeoff` is not supported and no expression evaluation can be performed. Example:

```
/
tsys bologna tatm=5 ft=6.5 tau0=0.1 trec = 120 /
.
.
/
```

Since the standard ANCAL input file does not contain information about polarization, source changes, and weather the following parameters only work with VLBA calibration files: **polarization, slewtime, tatmavg, tatmft, tatmoff, avgchan, weatherfile**. Experiments with multiple sources, multiple channels, or dual polarizations must have the calibration information in the TSM tsys section format (OPACOR can read only one channel from an ANCAL input file).

OPACOR also performs flagging of the T_{sys} points (basically commenting or just leaving them out) based on the following rules: 1) if the time tag of a data point falls outside the time range for the current scan (VLBA cal file only); 2) if the T_{sys} standard deviation over channels (estimated for all rows in the cal file) exceeds 15 Kelvins (VLBA cal file only); 3) if one or more of the channels has a bad point (999.9); 4) if the estimated attenuation is less than 1 or more than 4. In addition, if the fraction of data points flagged on the grounds of item 4 exceed 20 percent, no T_{sys} modification or flagging is applied to that station. In this case the word NOCORR appears after the data points in the output file.

For experiments more than, say, 12 hours in duration it is advisable to run OPACOR multiple times with shorter timeranges (if possible during periods of stable weather) to get better estimates of the receiver temperatures. After consistent values for the receiver temperatures have been found they can be fixed, as described above, and the whole experiment processed on a single run.

References

Elgered, G. 1981, Empirical formulae for the effective temperature of the atmosphere in the frequency ranhe 20–100 GHz. Onsala Space Observatory Memorandum.

Press, W., Flannery, B., Teukolsky, S., Vetterling, W. 1988, Numerical Recipes in C, Cambridge University Press, pp. 542–547.

FIG. 1

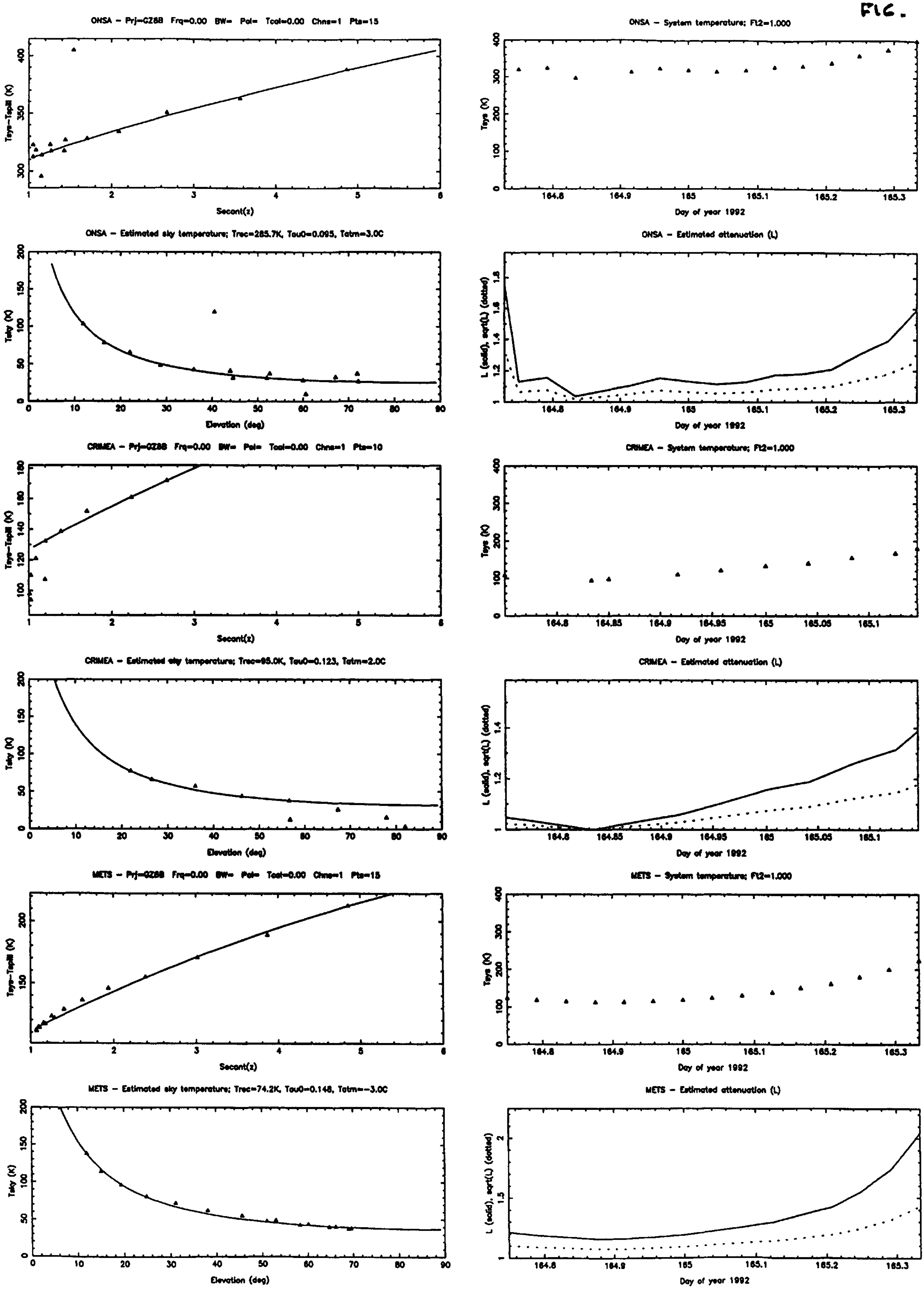

ONSA - Prj=GZ88 Frq=0.00 BW= Pol= Tcal=0.00 Chns=1 Pts=15
Tsys-Tspill (K)
Secant(z)
ONSA - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
ONSA - Estimated sky temperature; Trec=285.7K, Tau0=0.095, Tatm=3.0C
Tsky (K)
Elevation (deg)
ONSA - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992
CRIMEA - Prj=GZ88 Frq=0.00 BW= Pol= Tcal=0.00 Chns=1 Pts=10
Tsys-Tspill (K)
Secant(z)
CRIMEA - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
CRIMEA - Estimated sky temperature; Trec=95.0K, Tau0=0.123, Tatm=2.0C
Tsky (K)
Elevation (deg)
CRIMEA - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992
METS - Prj=GZ88 Frq=0.00 BW= Pol= Tcal=0.00 Chns=1 Pts=15
Tsys-Tspill (K)
Secant(z)
METS - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
METS - Estimated sky temperature; Trec=74.2K, Tau0=0.148, Tatm=-3.0C
Tsky (K)
Elevation (deg)
METS - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992

FIG. 2

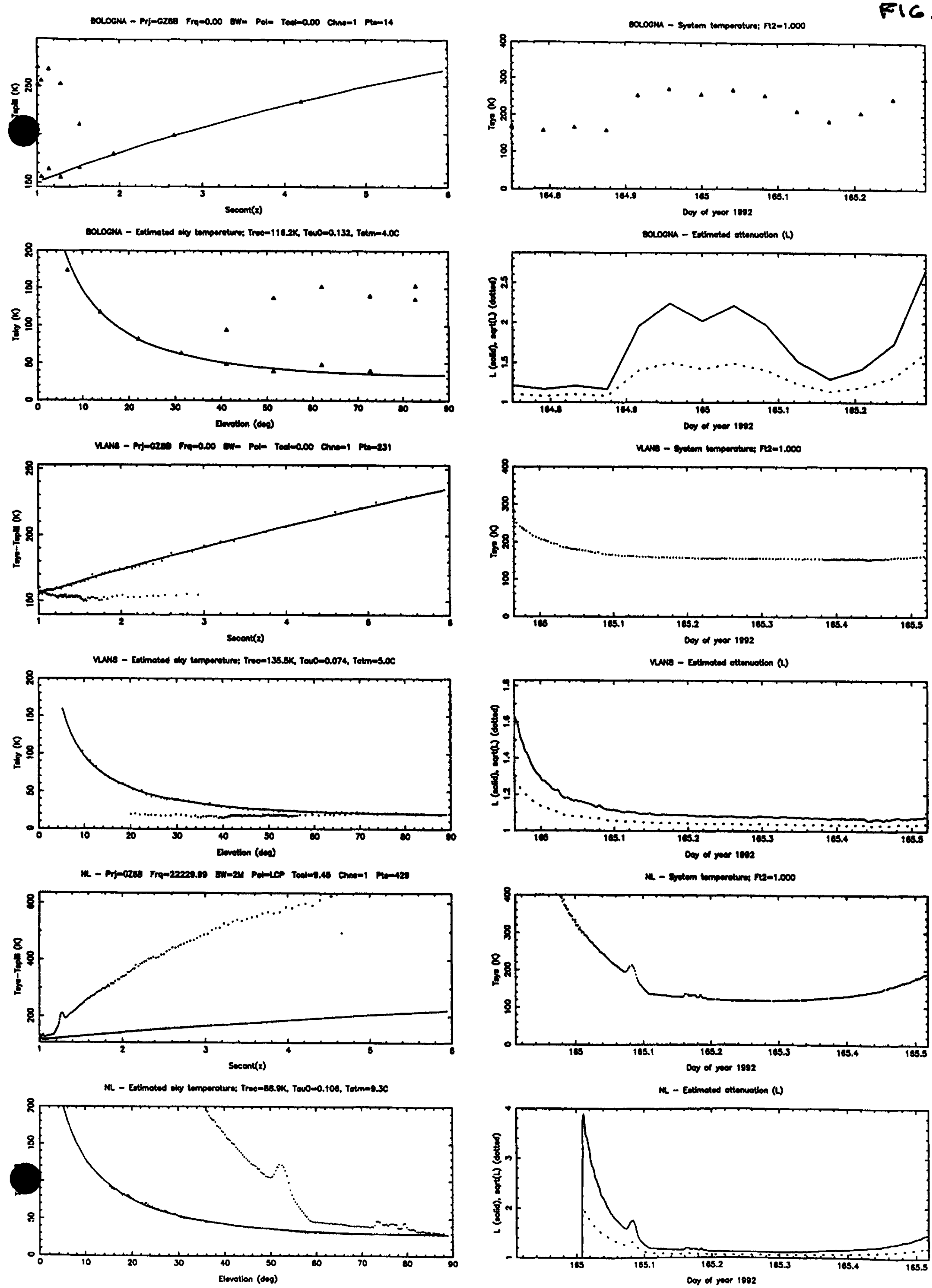
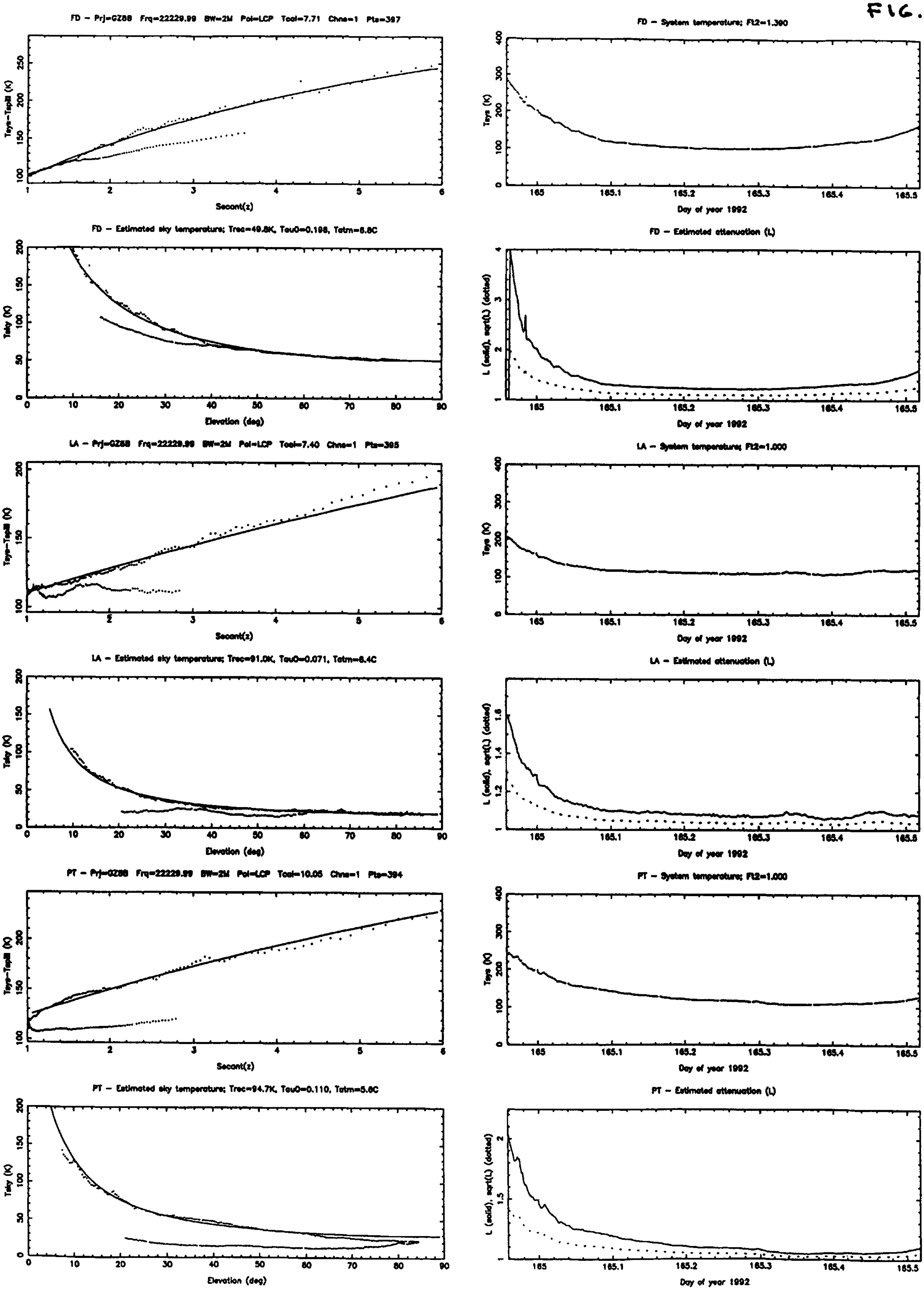

BOLOGNA - Prj=GZ8B Frq=0.00 BW= Pol= Tcal=0.00 Chns=1 Pts=14
Tsys-Tspill (K)
Secant(z)
BOLOGNA - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
BOLOGNA - Estimated sky temperature; Trec=116.2K, Tau0=0.132, Tatm=4.0C
Tsky (K)
Elevation (deg)
BOLOGNA - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992
VLA NS - Prj=GZ8B Frq=0.00 BW= Pol= Tcal=0.00 Chns=1 Pts=231
Tsys-Tspill (K)
Secant(z)
VLA NS - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
VLA NS - Estimated sky temperature; Trec=135.5K, Tau0=0.074, Tatm=5.0C
Tsky (K)
Elevation (deg)
VLA NS - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992
NL - Prj=GZ8B Frq=22229.99 BW=2M Pol=LCP Tcal=9.45 Chns=1 Pts=429
Tsys-Tspill (K)
Secant(z)
NL - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
NL - Estimated sky temperature; Trec=88.9K, Tau0=0.106, Tatm=9.3C
Elevation (deg)
NL - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992

FIG. 3



FD - Prj=GZ88 Frq=22229.99 BW=2M Pol=LCP Tcal=7.71 Chns=1 Pts=397
Tsys-Tspill (K)
Secant(z)
FD - System temperature; Ft2=1.390
Tsys (K)
Day of year 1992
FD - Estimated sky temperature; Trec=49.8K, Tau0=0.198, Tatm=8.8C
Tsky (K)
Elevation (deg)
FD - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992
LA - Prj=GZ88 Frq=22229.99 BW=2M Pol=LCP Tcal=7.40 Chns=1 Pts=395
Tsys-Tspill (K)
Secant(z)
LA - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
LA - Estimated sky temperature; Trec=91.0K, Tau0=0.071, Tatm=6.4C
Tsky (K)
Elevation (deg)
LA - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992
PT - Prj=GZ88 Frq=22229.99 BW=2M Pol=LCP Tcal=10.05 Chns=1 Pts=394
Tsys-Tspill (K)
Secant(z)
PT - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
PT - Estimated sky temperature; Trec=94.7K, Tau0=0.110, Tatm=5.6C
Tsky (K)
Elevation (deg)
PT - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992

FIG. 4

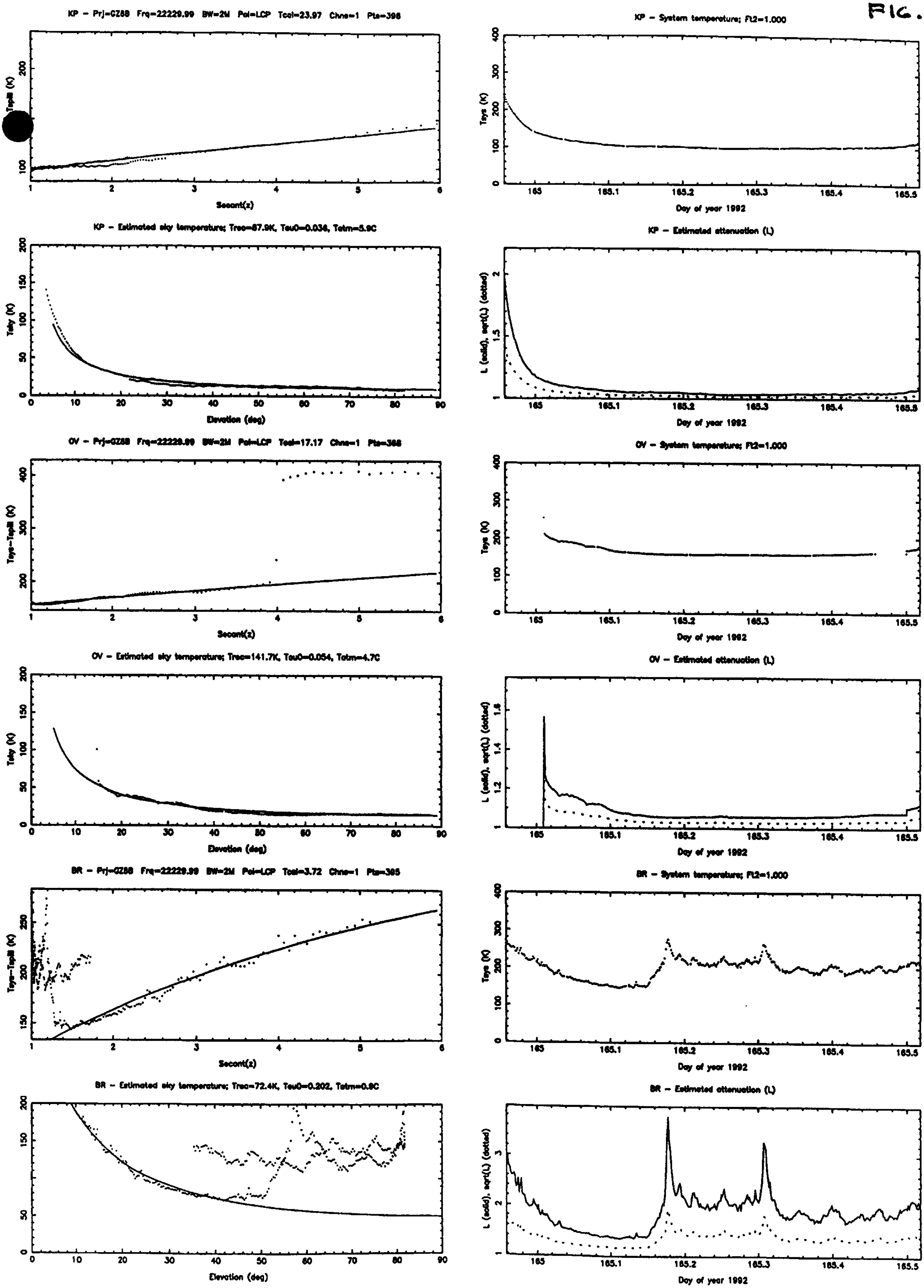
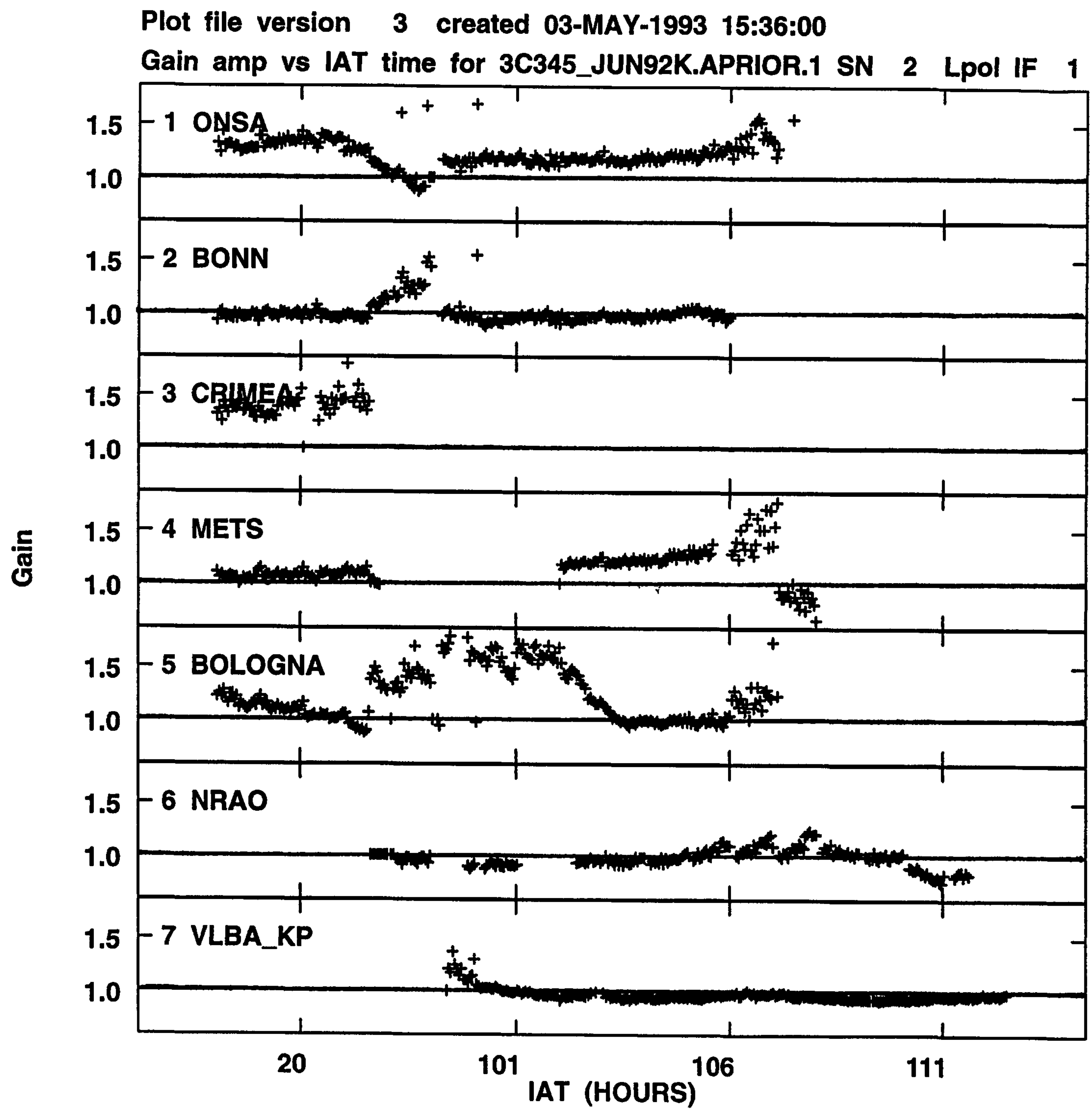
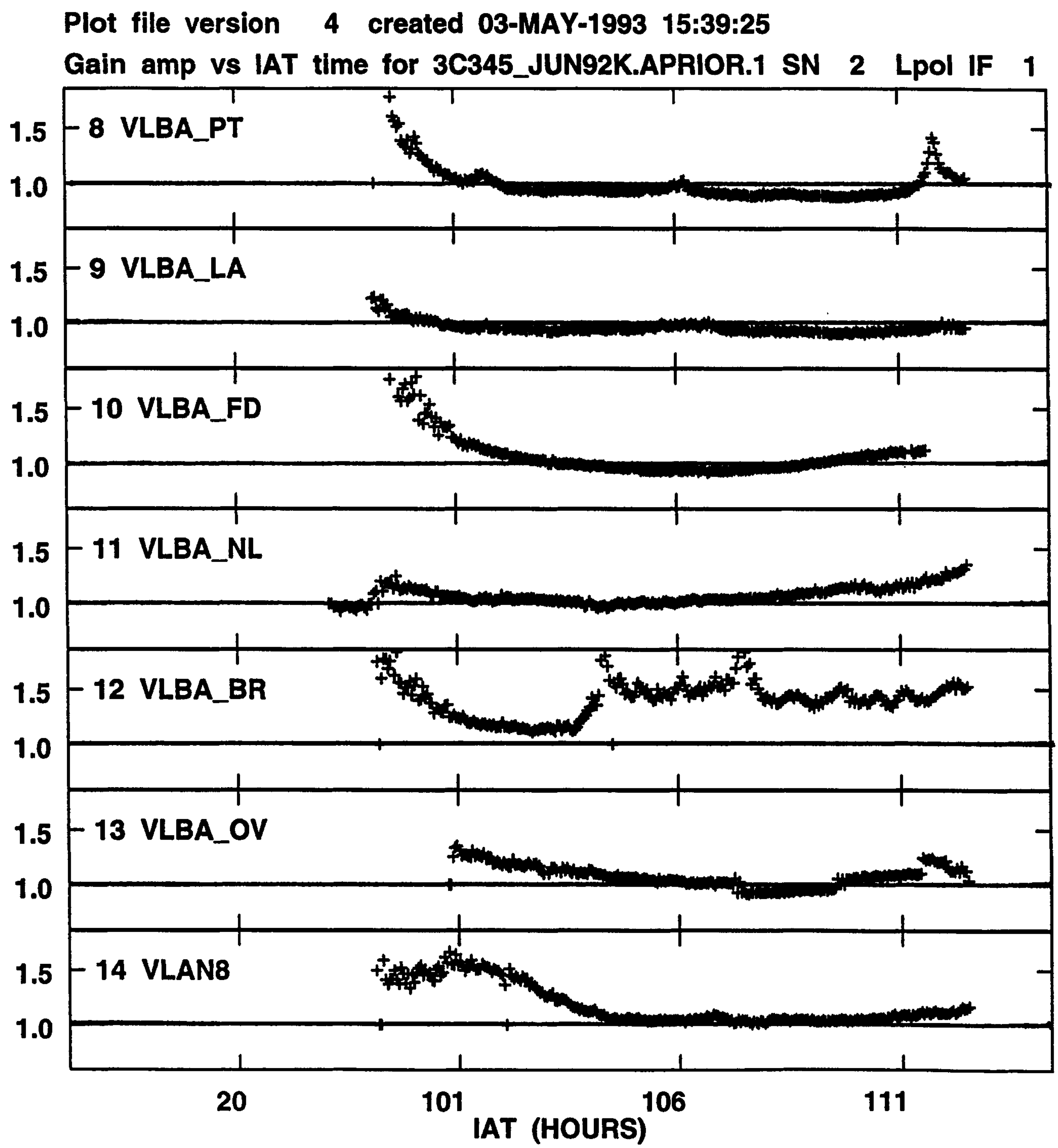

KP - Prj=GZ8B Frq=22229.99 BW=2M Pol=LCP Tcal=23.97 Chns=1 Pts=398
Tsys-Tspill (K)
Secant(z)
KP - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
KP - Estimated sky temperature; Trec=87.9K, Tau0=0.036, Tatm=5.9C
Tsky (K)
Elevation (deg)
KP - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992
OV - Prj=GZ8B Frq=22229.99 BW=2M Pol=LCP Tcal=17.17 Chns=1 Pts=368
Tsys-Tspill (K)
Secant(z)
OV - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
OV - Estimated sky temperature; Trec=141.7K, Tau0=0.054, Tatm=4.7C
Tsky (K)
Elevation (deg)
OV - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992
BR - Prj=GZ8B Frq=22229.99 BW=2M Pol=LCP Tcal=3.72 Chns=1 Pts=385
Tsys-Tspill (K)
Secant(z)
BR - System temperature; Ft2=1.000
Tsys (K)
Day of year 1992
BR - Estimated sky temperature; Trec=72.4K, Tau0=0.202, Tatm=0.9C
Elevation (deg)
BR - Estimated attenuation (L)
L (solid), sqrt(L) (dotted)
Day of year 1992

FIG. 5



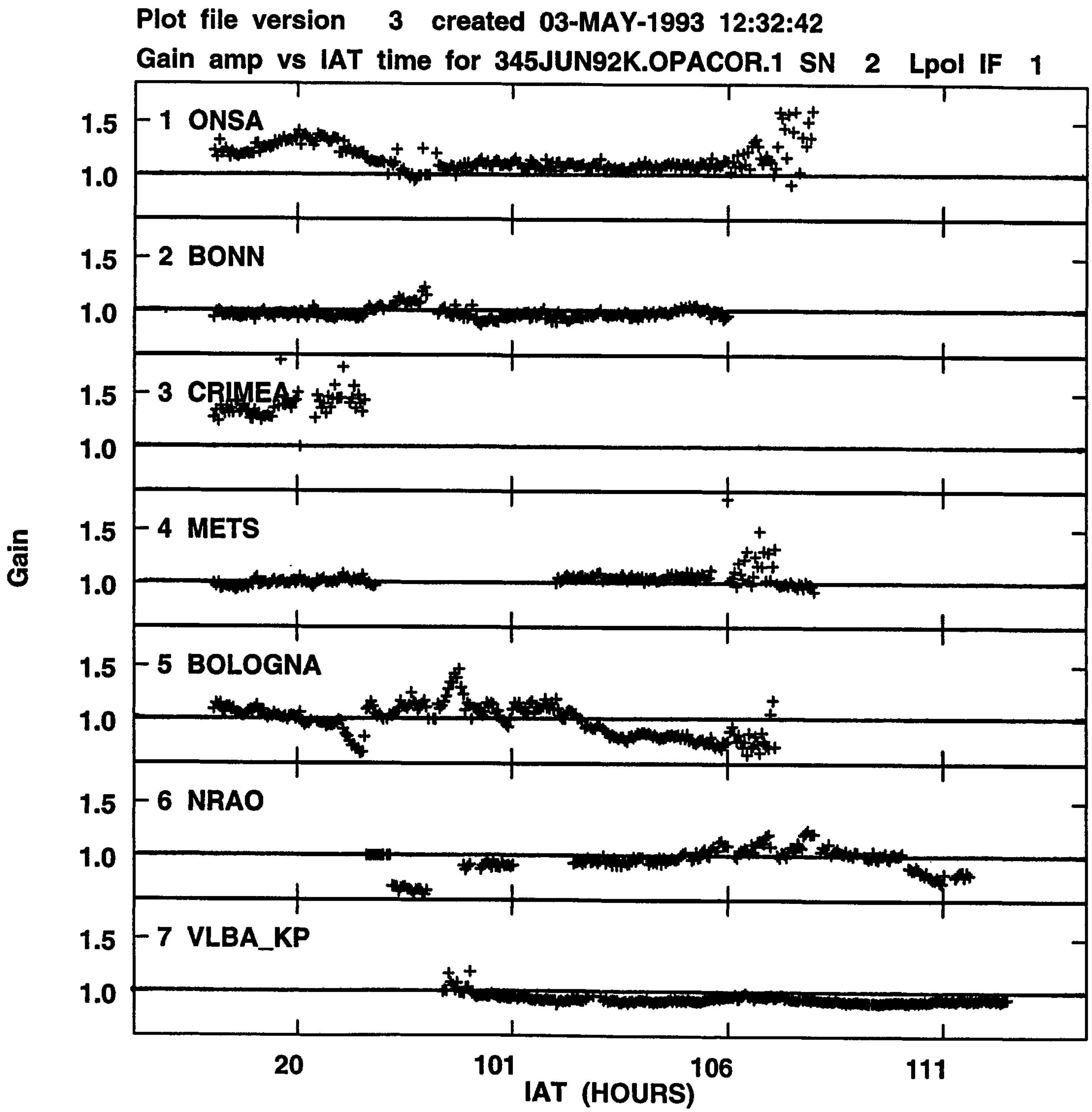
Plot file version 3 created 03-MAY-1993 15:36:00
Gain amp vs IAT time for 3C345_JUN92K.APRIOR.1 SN 2 Lpol IF 1
Gain
1.5
1.0
1 ONSA
2 BONN
3 CRIMEA
4 METS
5 BOLOGNA
6 NRAO
7 VLBA_KP
20
101
106
111
IAT (HOURS)

FIG. 6



Plot file version 4 created 03-MAY-1993 15:39:25
Gain amp vs IAT time for 3C345_JUN92K.APRIOR.1 SN 2 Lpol IF 1
8 VLBA_PT
9 VLBA_LA
10 VLBA_FD
11 VLBA_NL
12 VLBA_BR
13 VLBA_OV
14 VLAN8
1.5
1.0
20
101
106
111
IAT (HOURS)

FIG. 7



Plot file version 3 created 03-MAY-1993 12:32:42
Gain amp vs IAT time for 345JUN92K.OPACOR.1 SN 2 Lpol IF 1
Gain
1.5
1.0
1 ONSA
2 BONN
3 CRIMEA
4 METS
5 BOLOGNA
6 NRAO
7 VLBA_KP
20
101
106
111
IAT (HOURS)

FIG. 8

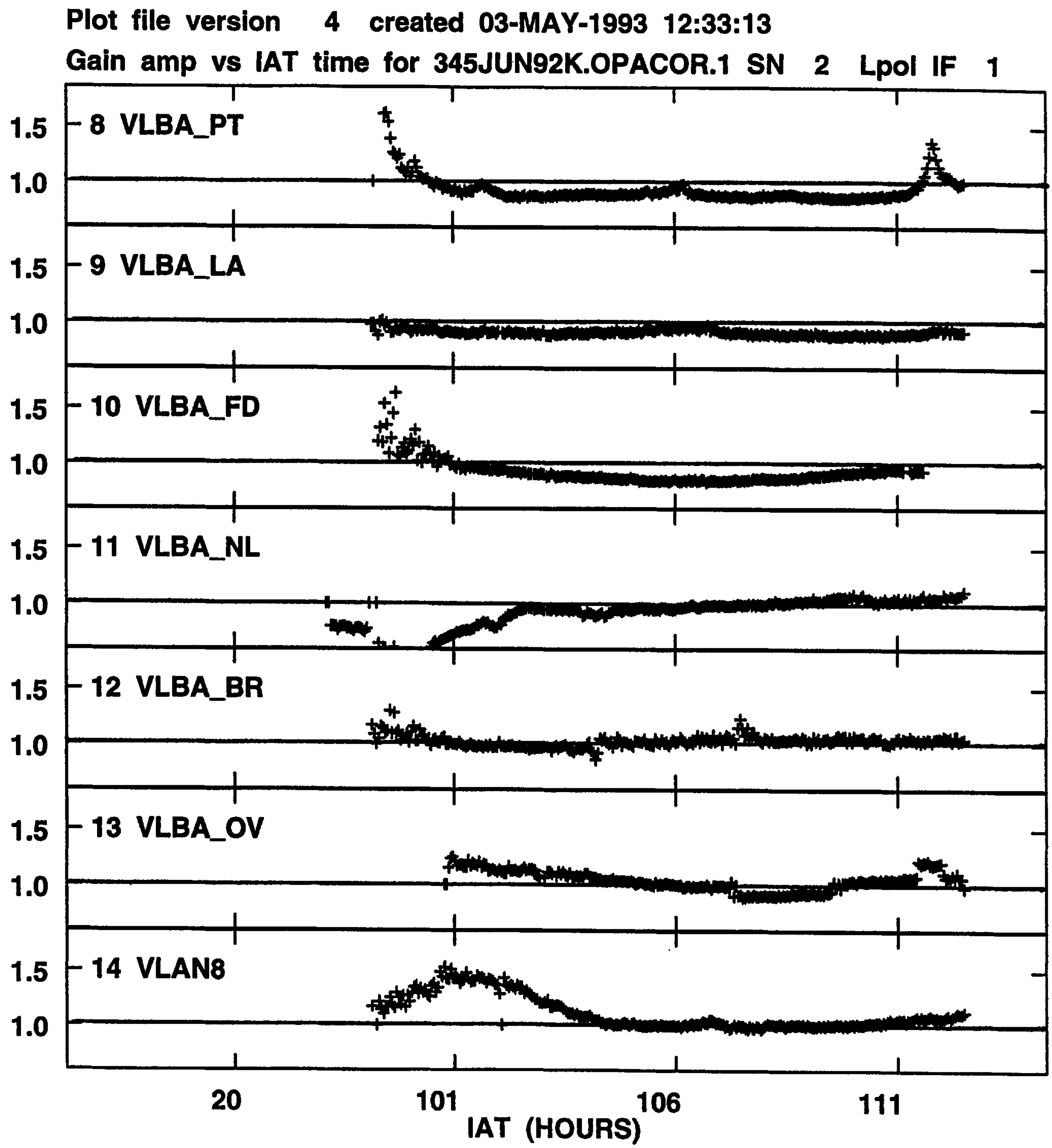
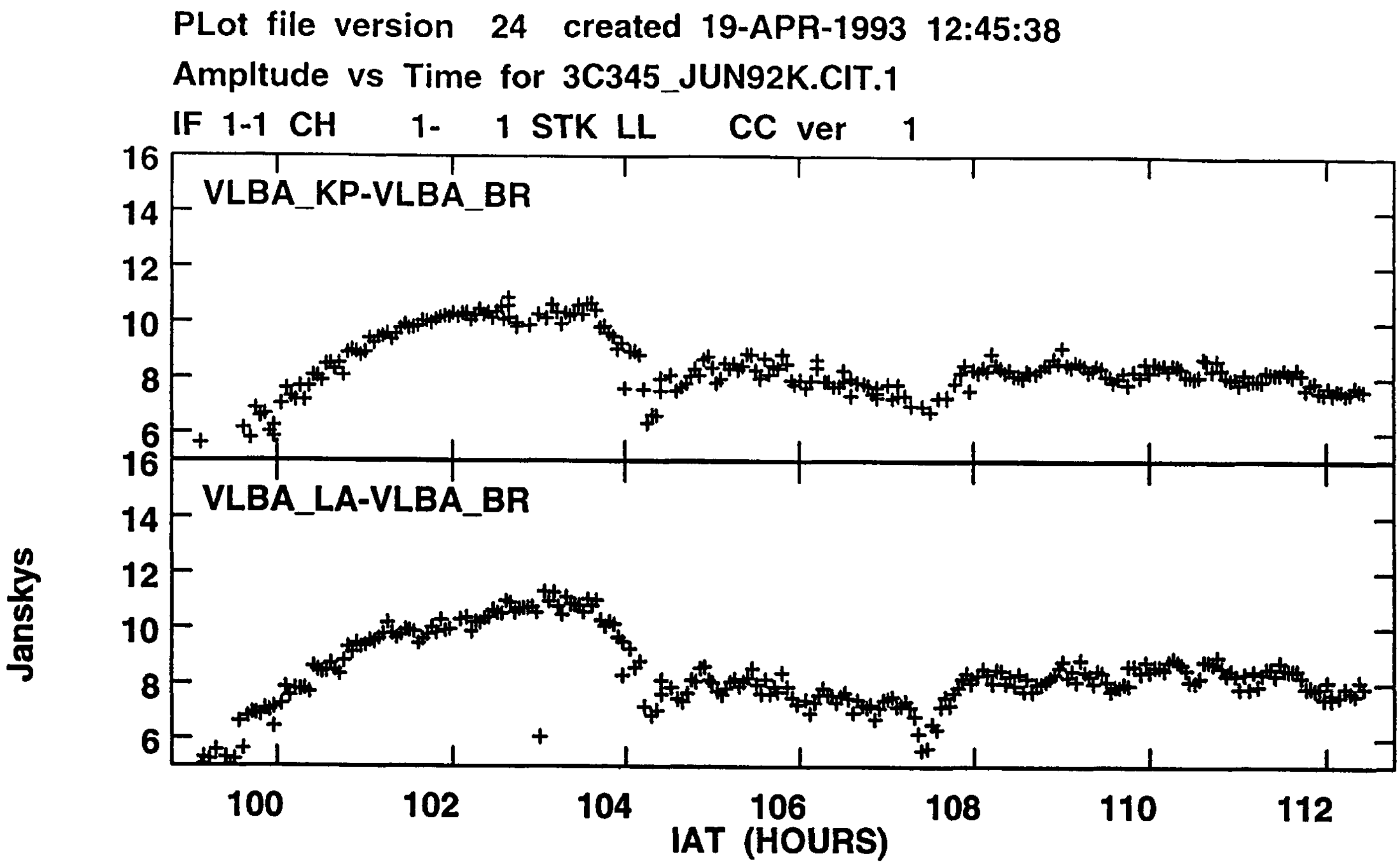
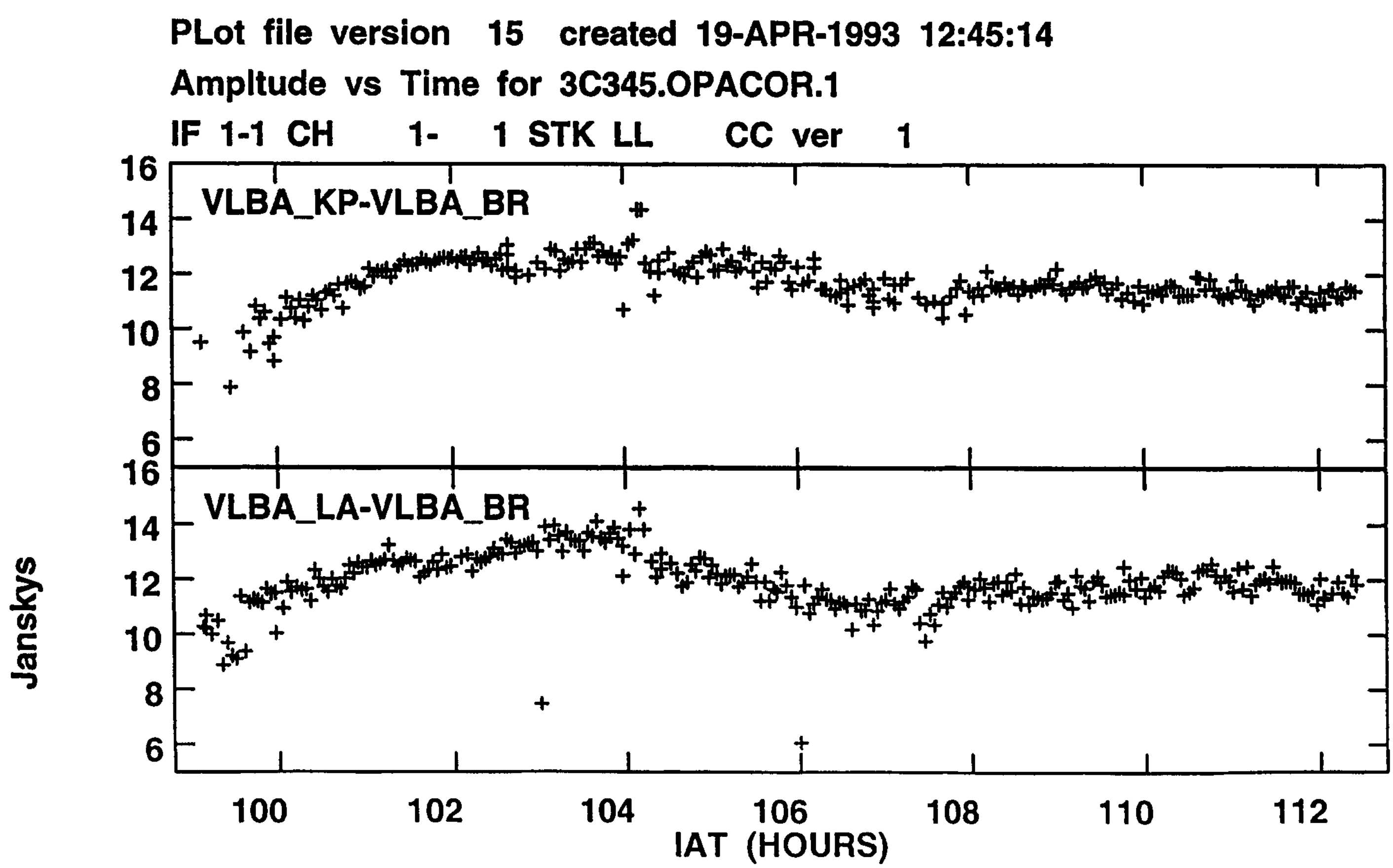

Plot file version 4 created 03-MAY-1993 12:33:13
Gain amp vs IAT time for 345JUN92K.OPACOR.1 SN 2 Lpol IF 1
8 VLBA_PT
9 VLBA_LA
10 VLBA_FD
11 VLBA_NL
12 VLBA_BR
13 VLBA_OV
14 VLAN8
1.5
1.0
20
101
106
111
IAT (HOURS)

FIG. 9


PLot file version 24 created 19-APR-1993 12:45:38
Ampltude vs Time for 3C345_JUN92K.CIT.1
IF 1-1 CH 1- 1 STK LL CC ver 1
VLBA_KP-VLBA_BR
VLBA_LA-VLBA_BR
Janskys
IAT (HOURS)


PLot file version 15 created 19-APR-1993 12:45:14
Ampltude vs Time for 3C345.OPACOR.1
IF 1-1 CH 1- 1 STK LL CC ver 1
VLBA_KP-VLBA_BR
VLBA_LA-VLBA_BR
Janskys
IAT (HOURS)