AIPS Data Analysis Training
Step-by-step recipe

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Contents

Chapter 1

Introduction

1.1   About this AIPS tutorial

This document is used for helping the tutorial in Astronomical Image Processing System (AIPS) data reduction practice, which is planned for people who what to use AIPS for their actual scientific works. Because an AIPS tutorial usually expected has a limited period, say shorter than five days in this tutorial, people who attend the tutorial are strongly recommended to understand theoretical concepts of Very Long Baseline Interferometry (VLBI), data correlation (delay tracking, fringe stopping, etc.) and output data obtained from the correlators before or after the tutorial. A special course for beginners of VLBI as well as radio astronomy may be provided by the author in Kagoshima University using AIPS automatic pipeline (e.g. [20]). To understand VLBI itself and theoretical concepts in detail, as well as individual functions in AIPS programs, several suitable textbooks have already been published ([22, 23]; Prof. T. Sasao's lecture text; K. Wajima's text [24]). This document describes connections between individual AIPS procedures and their suitable citations (shown in the *Bibliography*), which should be read during or after the AIPS tutorial. Install of AIPS is also skipped in this tutorial except for the part which should be understood by computer administrators who installs AIPS and give the users several permission (see section A.1).

1.2   Goal of this AIPS tutorial

Topics described in this document mainly focuses on practical matters in AIPS data reduction. Figure 1.1 presents a global flow chart of the AIPS tutorial. At final stage, procedures to obtain some scientific information are described (in chapter 16). Thus this tutorial assumes full analysis of VLBI data with AIPS. Most of the tutorial shall be based on practices using AIPS machines. Students shall read this document to understand purposes and fundamental functions of the individual AIPS procedures. How to input commands shall be found in other documents (e.g. [24]). However, such documents often do not cover topics about data reduction of spectral line (maser) source data, which are covered in this documents. Note that final AIPS outputs are not final scientific results. More corrections are necessary, which are also described in 16.

In addition, note that there is no VLBI data prepared specially for this AIPS tutorial. Figures shown in this documents are cited from many but different VLBI projects of the author's. The author, or tutor of this tutorial, is always using *real VLBI data* that have not only potential to be published in a specific scientific journal but also difficulty and problems in data reduction. Through this tutorial, students shall understand how to check or judge data quality and correct procedures in the data reduction.

1.3   Task, verb and adverbs in AIPS

1.3.1   Calling tasks and verbs

Task is an AIPS program, which is called by typing `TASK` ' (*task name*) ' at first, then executed by typing `GO`. *Verb* is an AIPS command, which is executed by directly typing its own verb name. The table 1.1 shows a list of the verbs. *Adverb* is an parameter, which is input by a user and called in some of tasks and verbs.

A user, therefore, should note that the meaning of an adverb in one task is different from that in the other tasks.

Input adverbs in a task or a verb can be checked by typing `INP`. Adverbs input in a task can be recorded by typing `TPUT` *task name*. Adverbs recorded by `TPUT` or set when executing the task can be called by typing `TGET` *[task name]*. A combination of a task and its adverbs can be recorded by typing `PUT` *[your specified name]*. It can be called by typing `GET` *[your specified name]*. A task can be aborted by typing `ABORT`. `HELP` and `EXPLAIN` show explanation of a task or an verb. Table 1.1 shows a list of the verbs. All tasks and verbs can be recognized by typing only first three characters or more of their own names.

1.3.2   AIPS catalog files

AIPS has `AIPS catalog files` (see also section 3.1), which are called by adverbs `INDISK`, `IN2DISK`, etc., `GETN`, `GET2N`, etc., and `OUTDISK`, `GETO`. These adverbs are used in different purposes, in specifying a catalog file as, e.g., *input* or *output* catalog file.

When a task is aborted by typing `ABORT`, status of the used catalog files should be checked by typing `UCAT` (for UV files), `MCAT` (for image files) or `PCAT` (for all files). If a status flag of a file is either `WRITE` or `READ`, then the status should be cleared by typing `GETN` *catalog number* `; CLRSTAT`. Otherwise any task and verb is invalid for the file having a status flag.

An AIPS file is destroyed by typing `ZAP`. Header information of a AIPS file can be read by typing `IMHEADER`. When removing only extension tables (see section 4.1), type `EXTDEST`.

1.4   RUN file in AIPS

In AIPS, a user specifies tasks and inputs verbs and adverbs *interactively*. It is quite convenient, therefore, to prepare a (electric) text file describing a sequence of input strings. The author does not recommend to record the input strings in a notebook written by a pen or a pencil, because the strings in the notebook are often different from those actually input in AIPS and the notebook is often useless. On the other hand, strings written in a text file are easily copied and pasted in the AIPS command-input window. This is helpful to find some problem just before executing AIPS tasks.

A *RUN* script describes such a sequence of strings in a grogram from, which is controlled by a grammar similar to BASIC/FORTRAN language. Looping, case selection are valid in the *RUN* file. Special adverbs can be defined and specified by a user. Some *RUN* file has been developed as *a pipeline script* (see section 17.2).

A *RUN* file has a name such as *[RUN filename].[user ID (hexadecimal)]*. This should be put in the $RUNFIL directory or , unless $RUNFIL is specified, in `$AIPS_ROOT/$AIPS_VERSION/RUN`. This is called and executed by typing `RUN` *[your RUN file]*.

1.5   How to start AIPS?

A user needs the following action items for smoothly starting AIPS.

- Not only your login account for an AIPS machine but also your AIPS ID number are necessary (contact to the machine and AIPS administrator).

- If a user is using the machine without AIPS, type `xhost +` to add any machine to those having permission for transporting working windows to the user's machine.

- Login an AIPS machine, and set the environment `DISPLAY`. Not that some LINUX machine might has to skip this step.

- Type the script described in chapter A.2.1. If a user wants to skip this step every time, follow the procedure described in chapter A.2.1.

- Type `aips tv=local`. Note that the file `aips` should be symbolic-linked to the AIPS execution file `START_AIPS` in the AIPS home directory and the directory should be recognized in every location by the user (by setting the user's path).

Table 1.1: AIPS verbs frequently used.

Verb	Function
ABORT	Abort the task currently running.
ALTDEF	Define velocity information in the header information.
ALTSWTCH	Switch between velocity and frequency in the header information.
CELGAL	Convert between celestial and galactic coordinate in the header.
CLRMSG	Clear messages in the memory.
CLRNAME	Clear first input file name information (INDISK, INNAME, INCLASS, INSEQ).
CLRNAME	Clear first output file name information (OUTDISK, OUTNAME, OUTCLASS, OUTSEQ).
CLRSTAT	Clear a status flag of the AIPS file.
DISMOUNT	Dismount a tape drive (DAT, Exabyte, etc.) to unset a tape.
EXIT	Exit AIPS.
EXTDEST	Destroy an extension table in the AIPS file.
EXPLAIN	Show explanation of a task or a verb in more detail than HELP.
FREESPAC	Show disk spaces.
GET	Save a task/adverbs combination.
GETHEAD	Get parameters from the header information.
GETN	Set an AIPS file in INDISK, INNAME, INCLASS, INSEQ by specifying an AIPS catalog number.
GETO	Set an AIPS file in OUTDISK, OUTNAME, OUTCLASS, OUTSEQ by specifying an AIPS catalog number.
GO	Execute a task.
HELP	Show explanation of a task or a verb.
EHEX	Show the current AIPS ID in a hexdecimal string.
IMHEADER	Show a header of the AIPS file.
IMSTAT	Perform image statistics in a selected box.
INP	Show a list of adverbs input in the task.
MCAT	Show a list of image AIPS files (catalog).
MOUNT	Mount a tape drive (DAT, Exabyte, etc.) to set a tape.
PCAT	Show a list of all AIPS files (catalog).
PRTHI	Print a history of the AIPS file on a printer, a display or a file.
PRTMSG	Print messages in the memory onto a printer, a display or a file.
PUT	Load a task/adverbs combination.
PUTHEAD	Put parameters to the header.
RENAME	Rename an AIPS file.
RESTORE	Initialize tasks and adverbs.
REWIND	Rewind the tape mounted.
RUN	Read a *RUN* file.
SPY	Show current task status.
TASK	Call a task.
TVAL	Display an image on the TV Server.
TVBOX	Set a box on the TV Server.
TVCLEAR	Clear the TV Server.
TVLABEL	Put labels on the TV Server.
TVINIT	Initialize the TV Server.
TVMOVIE	Display an image cube on the TV Server.
UCAT	Show a list of UV AIPS files (catalog).
WAIT	Wait the next task until finishing the task currently running.
ZAP	Remove an AIPS file.

Global flowchart for AIPS tutorial

For data analysis of maser sources

Introduction about AIPS
(Chapter 1)

Preparing data
(Chapter 2)
FITS, flag, gain, Tsys

Loading UV data
(Chapter 3)
FITLD/(MSORT)/INDXR

Watching UV data
(Chapter 5)
LISTR/DTSUM/PRTAN
POSSM/VPLOT/UVPLT/COHER

**Strategy on observation
and calibration (1)**
(Chapter 5)

Fundamental calibration
(Chapter 6)
UVFLG/ANTAB/APCAL
AVSPC/FRING

**Self-calibration and
hybrid mapping**
(Chapeter 7)
SPLIT/CALIB/IMAGR
IMEAN/IMSTAT/PRTCC/TVALL

Lecture part

AIPS practice

Data handling

**Strategy on observation
and calibration (2)**
(Chapter 8)

Advanced calibration
(Chapter 9)
BPASS/SETJY/CVEL/ (SPLIT/ACFIT)

Watching maser emission
(Chapeter 10)
POSSM/VPLOT/UVPLT

Maser calibration
(Chapter 11)
IBLED/FRING/SPLIT/CALIB/IMAGR

Search for maser emission
(Chapter 12)
FRMAP/SPLIT/IMAGR
TVMOVIE/IMEAN

Creating image cubes
(Chapter 13)
SPLIT/IMAGR/BLANK/SQASH

Getting physical parameters
(Chapter 14)
IMEAN/IMSTAT/JMFIT/SAD

Data backup
(Chapter 15)
TASAV/FITTP

Scinentific analysis
(Chapter 16)

Summary
(Chapter 17)

Figure 1.1: Global flow chart of the AIPS tutorial. Break lines indicate breaks of daily AIPS practice and lecture. The AIPS tutorial expects a five-day course. Grey parts will be skipped in the tutorial.

Chapter 2

Preparing data

Generally speaking, astronomical VLBI data reduction requires the following items from used telescopes and a VLBI correlator. Formats in flag and calibration files that are read in AIPS are seen in the VLBA (aspen) and the EVN (archive) homepages. They are used at the stage described in chapter 6.

2.1 Visibility data

To make data analysis with AIPS, visibility data are contained in *FITS (Flexibility Image Transport System)* format. The data consists of not only complex visibilities but also the following items adopted in the correlation.

- Weights that indicate quality of the visibilities, which may be defined on basis of tape playback and correlator performance.

- (u, v, w) values, but which may be directly used not for data analysis itself but for plotting data in AIPS.

- Delays, delay rates and delay accelerations.

- Station coordinates and source coordinates with there references.

- Frequency and spectral channel setups.

- Scan information (time table of scans).

2.2 Flag information

Bad data, which are contaminated because of inappropriate operation, poor weather or system condition and other reasons, severely affect final results in source images. The flags are read in the AIPS task `UVFLG`. The bad data that should be flagged out are divided into two sorts as follows.

2.2.1 Expected flags

They can be made when making an observation schedule. In fact, NRAO's SCHED has a function to generate flags in this case.

(1) Dead data that are generated, for example, during time when antennas are not tracking target sources because of changing the target sources while data recording has already started. Antenna operation limit also creates such invalid data. They can be expected on basis of antenna specification and performance.

(2) Visibilities that are located very close to IF band edges usually have poorer quality than those in other band range. At some of frequency range may have artificial radio interferences.

2.2.2 Accidental flags

They are generated by operators by hand or operating system to operate antennas and backend during an observation. There are major reasons to create such situations.

(1) Strong wind, snow, and thunders that makes antenna operation interrupted.

(2) Artificial accidents, e.g. wrong antenna operation and system troubles.

2.3 Calibration data

They are generated for each of telescopes or baselines to calibrate visibility amplitudes and phase. They are read in the AIPS task `ANTAB`. The following items are essential for this purpose.

2.3.1 Antenna gains

An antenna gain is defined in AIPS as the *degrees per flux unit* (K/Jy) $DPFU = \frac{A_e}{2k_B}$, where A_e is an effective aperture of the telescope k_B Boltzman's constant. Because the effective aperture depends on antenna elevation, this is usually described as a polynomial function. Coefficients of the DPFU function can be specified in the gain tables.

2.3.2 System noise temperatures

System noise temperature varies rapidly, especially at higher frequency because mainly of variation in weather condition. In an advanced case, because of necessity, the temperatures are measured every 10 seconds. This is possible, for example in VERA system, by monitoring an electric power level toward a target source. Sometimes, usually during the target sources are changed, an electric power levels should be measured towards an absorber with its known temperature. The system temperature is measured as difference of power levels between towards the target and the absorber.

2.3.3 Visibility phase calibration tables

There are a few reason to insert phase calibration information. One of the most important reasons is phase compensation for atmospheric phase fluctuation. In VERA system, calibration tables to estimate differential phase delay between dual beams are provided. Even in KVN that has no dual-beam system, other calibration tables, for example which are provided by water vapor radio meters, may be effective.

Chapter 3

Loading UV data

Figure 3.1 describes a flow of AIPS tasks for data loading (`FITLD`) and for data transformation (`MOSRT`). Adverbs input in each of the tasks can be seen by typing `INP` *[task name]* or `HELP` *[task name]*. Here, some of important tasks and adverbs are described.

3.1 File name

The name of an AIPS file, or a catalog file, consists of three parts: *NAME, CLASS* and *SEQUENCE. NAME* usually specifies what the file is, e.g. project code, source name. *CLASS* has only six characters and usually specifies which type the data is. The name of the task that finally produced the file is usually specified in *CLASS. SEQUENCE* describes the order of similar kinds of files.

Note that all characters in a string are automatically capitalized when the string is bracketed with single-quotation marks (') at the beginning and the end of the string. If the string does not have a single-quotation mark after it, both of capital and lower-case characters are recognized.

3.2 Time interval in the calibration (`CL`) tables

Data calibration in AIPS (see chapter 5) is made by updating a calibration table (`CL`) see section 4.1, which is a time/baseline series of complex gain factors. A time interval of the series should be short enough to compensate visibility phase and amplitude variation. However, the time interval shorter shorter than the parameter period of the correlator output is meaningless. This time interval is specified in the adverb `CLINT` in unit of minute in the task `FITLD`. If the `CL` table is removed then created in the task `INDXR`, the adverb `APARM(3)` specifies the time interval. Usually `CLINT`$\simeq$1/60-5/60 (min).

3.3 `MSORT`: Sorting the UV data into time-baseline order

If the original FITS data do not have time-baseline order, this task should be executed. Sometimes `MSORT` should be executed before concatenating multiple FITS files with the task `DBCON` otherwise `MSORT` consumes extremely long time without successful execution.

3.4 `INDXR`: Creating an index (`NX`) table

An index (`NX`) table (see also section 4.1 maintains the information including scans, source coordinates, frequency setups and so on. This table is necessary for executing other AIPS tasks. The first three parameters in `CPARM` specify the maximum time gap between scans, the maximum scan length and the time interval of the `CL` table.

FITS files Block size
2880, 6250, 12880
bytes

Where is the FITS?

On DAT tape
MOUNT

FITLD

Where is the FITS?

On DAT tape
DISMOUNT

MSORT

DBCON Sometimes necessary
for concatenating
multiple UV data

INDXR **NX1** **CL1**

MERGECAL (in new VLBA data)
concatenating attached
TY, GC and FG table
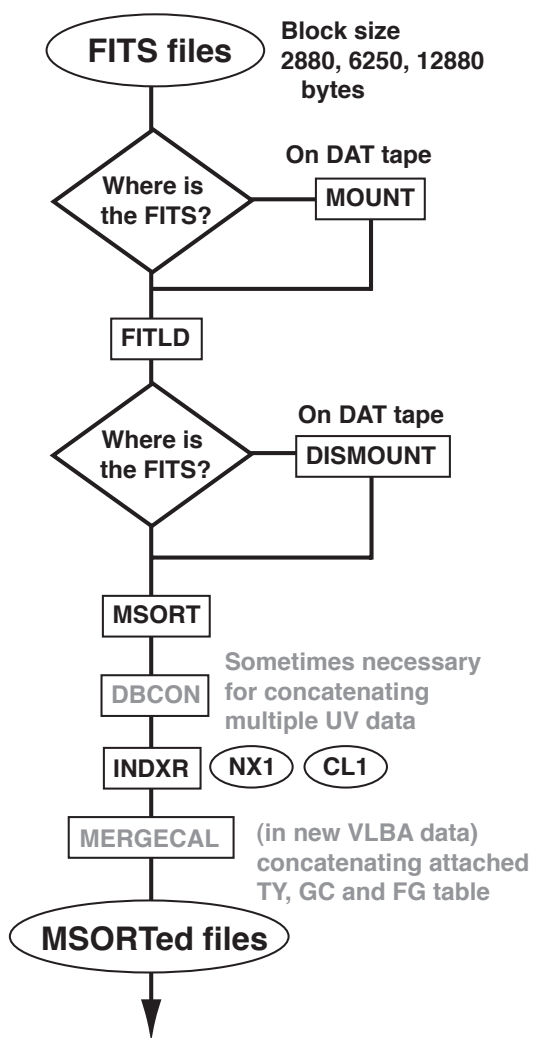
MSORTed files

Figure 3.1: Flow chart of the part that describes loading AIPS UV data.

Chapter 4

Watching UV data

4.1 Extension tables

AIPS UV data consists of visibilities, weights, (u, v, w) values and the *extension tables*. The existence of the extension tables can be checked with the verb `IMHEAD` (showing the file header). The list of the extension tables are shown in the text [24]. The contents of them are displayed by using the tasks shown in table 4.1.

Table 4.1: AIPS extension tables and their displaying tasks.

Extension table	Contents	Task for display
NX	Scans, source coordinate, frequency setups	INDXR
AN	Antenna parameters (coordinates, mounts, etc.)	PRTAN
CL	Complex gain factors, delays and rates calibrated	SNPLT, CLPLT
SN	Calibration solutions in amplitude, phase, delay and rate	SNPLT, TBOUT (in file)
BP	Complex or total-power bandpass characteristics	POSSM
TY	System noise temperatures of antennas	SNPLT
GC	Gains of antennas	SNPLT
PL	Plot file	LWPLA (in printer), TKPL (in TeK server)
HI	History table	PRTHI
CC	CLEAN components in the image cube	PRTCC
SU	Source information	???
FQ	Frequency setup	???

4.2 Scans, source information and frequency setups

The task `LISTR` with setting `OPTYPE='SCAN'` displays them.

- When setting `DOCRT=1` (or positive number), they appear in the terminal window inputting commands.

- When setting `DOCRT=-1` without specifying `OUTPRINT`, they are printed out in a printer.

- When setting `DOCRT=-1` with specifying `OUTPRINT`, they are recorded in the file specified in `OUTPRINT`.

4.2.1 About scans

The scans are displayed their time ranges in time order. In a maser source observation, the scans may consists not only of scans towards the target maser source but also of scans towards the following sources.

(1) Fringe finders:
   Bright continuum emission sources (QSOs) used for finding fringes in the first step of data correlation. These scans can also be used for obtaining complex bandpass characteristics (see caption 8 and section 9.1.

(2) Clock parameter calibrators:
Continuum sources scanned every 30-90 minutes to monitor clock parameters (residual delays and delay rates of individual antennas).

(3) Maser fringe finders:
Sometimes bight maser sources are observed at the beginning of the observation to check the frequency setups. They are not used in data reduction.

(4) Phase-reference sources:
If the target maser sources are too weak to be detected within a coherence time (shorter than 5 min for H_2O maser sources, see section 4.7), the phase-reference sources are scanned every period shorter than the coherence time followed by the target maser sources.

4.2.2 About sources

In the output of the task `LISTR`, the source information consists of the source coordinates (J2000.0), Stokes parameters (set to zero as defaults), the rest frequencies (set to the local frequencies as defaults) and the line-of-sight velocities (set to zero as defaults). Later, if necessary, they are specified by a user in the AIPS task `SETJY` (see section 9.2.1).

4.2.3 About frequency setup

The frequency setup is a sequence of IF channels having local frequencies, band widths and frequency resolutions of the spectral channels and upper-side or lower-side band information.

4.3 Quantity of the visibilities

The task `DTSUM` calculates and displays fractions of available visibilities in the individual baseline with respect to the expected numbers of visibilities. This task is useful for finding which antenna has the largest number of visibilities in the observation and is, therefore, suitable for a *reference antenna* (see section 5.3).

4.4 Antenna information

The task `PRTAN` presents antenna parameters contained in the `AN` table. The antenna coordinate (X, Y, Z) on the Earth at the observation epoch, type of antenna mount (azimuth-elevation, equatorial, etc.), and an axis offset are displayed.

4.5 Visibility along frequency and among IFs

The task `POSSM` displays amplitudes and phases of visibilities along frequency. This is useful mainly for finding maser emission in a number of spectral channels. Without any calibration, an integration period set in the adverb `SOLINT` should be shorter than an expected *coherence time* (see section 4.7). If choosing the all time range of the observation, a lot of spectra are generated from time to another. Therefore, it is appropriate to choose a time range in the adverb `TIMERANGE`.

4.5.1 Printing Spectra

When setting `DOTV=1`, the spectra are displayed on the AIPS TV server. When setting `DOTV=-1`, the spectra are saved in the plot (`PL`) files. In the task `LWPLA`, they are printed out on a printer without specifying the adverb `OUTFILE` or plotted in PostScript files with specifying the adverb `OUTFILE`. When specifying `OUTPRINT` in the task `POSSM`, the spectra are save in the text file specified in the adverb `OUTPRINT`.

Without any antenna selection, visibilities in all baselines are plotted and so many time is consumed. It is difficult to check data in all of the baselines. It is convenient to select on antenna that have highest sensitivity and most reliable performance as a *reference antenna* and to plots visibilities only in the baselines

including this reference antenna (see also section 5.3). This can be made by setting the adverb `ANTENNAS` to choose only the reference antenna.

At this stage, only spectral-channels and frequency axes are available for the horizontal axis. To use the line-of-sight velocity axis, a user should define the system of the velocity, which is described in section 9.2.1.

4.5.2 Total power spectra

By setting `APARM(8)=1`, total power spectra from auto-correlation data are displayed. At this stage, maser emission is found if the maser emission is enough bright. Usually, however, a maser emission peak is much weaker than a slope of the bandpass characteristics and too weak to be identified. Nevertheless the total power spectra are useful to find artificial radio interference that should be flagged out in data reduction. It is also understood that how severely the IF band edges lose sensitivity or have poor quality of visibility.

4.5.3 Cross-power spectra

By setting `APARM(8)=0`, cross power spectra from cross-correlation data are displayed. There are two types of integration, scalar average (`APARM(1)=0` and vector average (`APARM(1)=1`). The former is useful to find maser emission because this is similar to that made in total-power spectrum and even maser components having big position offsets can be detected.

The latter, on the other hand, has more information on the maser emission than the former. If maser components have big position offsets, they are weaken in the spectrum. By changing the adverbs `SHIFT` *R.A. offset, Decl. offset*, the spectrum varies in which the maser components close to the shifted delay-tracking center *(R.A. offset, Decl. offset)* appear without losing their visibility amplitudes. A coherence time can be also roughly estimated by changing the adverbs `SOLINT` and by checking loss of the visibility amplitudes.

Visibility phases in the spectral channels having maser emission have similar phases without their scattering. Therefore a user can see a smooth slope of the phases along frequency. In other word, detection of such phase slope is indicative of maser emission detection.

4.6 Visibility along time

The task `VPLOT` displays amplitudes and phases of visibilities along time. Different from `POSSM`, it is appropriate to set the adverb `SOLINT` to be much shorter than the coherence time for tracing amplitude and phase variation in detail.

Because task `VPLOT` averages visibilities among frequency channels, the averaged visibilities have smaller amplitudes at this stage because the visibilities before averaging have different phases and then smearing occurs. The removal of this smearing can be checked by comparing the `VPLOT` outputs between before and after *fringe-fitting* (see section 6.5.2).

4.7 Estimating a coherence time

A coherence time is a period for which visibilities can be integrated without reducing the visibility amplitude. Coherence loss occurs because of phase fluctuation due to the atmosphere and instability of the electric path in the signal transportation system. A coherence time is inversely proportional to observed frequency, empirically speaking 5–10 min at 5 GHz, 2–4 min at 22 GHz and 1–2 min at 43 GHz depending on weather condition. The coherence time can be measured with the task `COHER`.

Chapter 5

Strategy of observation and calibration (1)

Here planning a VLBI observation and strategy of data calibration are described.

A visibility obtained in a VLBI observation ρ_{ij}^{obs} in a baseline between the telescopes i, and j usually has a form of a *normalized cross-correlation coefficient* and calibrated to be V_{ij}^{cal} by multiplying a *complex gain factor* as follow,

$$V_{ij}^{cal} \quad = \quad g_{ij} e^{-\phi_{ij}} \rho_{ij}^{obs}, \tag{5.1}$$

$$g_{ij} \quad = \quad 2k_{\mathrm{B}} \sqrt{\frac{T_{\mathrm{sys},i} T_{\mathrm{sys},j}}{A_{\mathrm{e},i} A_{\mathrm{e},j}}} \quad = \quad \sqrt{\frac{T_{\mathrm{sys},i} T_{\mathrm{sys},j}}{DPFU_i DPFU_j}}. \tag{5.2}$$

where A_{e} and T_{sys} are an effective aperture and a system noise temperature of the telescope, respectively, k_{B} Boltzman's constant (see also equation of 15.1.6 of the text [24]). The amplitude of the gain factor is obtained in the fundamental procedure (see sections 6.4.1 and 6.4.2) and self-calibration more precisely (see chapter 7).

To understand the contents of a phase part of the complex gain factor, the following equations that describes a visibility phase, $\Delta\phi(\nu, t)$, obtained in actual VLBI observation in one baseline in detail (see also equations in chapter 12.5 of the text [23]) are useful.

$$\Delta\phi(\nu, t) \quad \simeq \quad \frac{2\pi\nu}{c}(\boldsymbol{D} + \boldsymbol{\sigma D}) \cdot \boldsymbol{\Delta s}(\boldsymbol{\nu}) + \phi^{\mathrm{str}}(\nu)$$

$$+ \quad 2\pi(\nu\tau^{\mathrm{inst}} + \sigma\nu^{\mathrm{LO}}\Delta t + \nu\tau^{\mathrm{atm}}) + \phi^{\mathrm{LO}} + \phi^{\mathrm{IF}}(\nu) + 2\pi n \tag{5.3}$$

$$\phi^{\mathrm{str}}(\nu) \quad = \quad arg\left[\int_{\boldsymbol{\Omega}} B(\boldsymbol{\sigma_{map}}, \nu) \exp(-\frac{2\pi\nu}{c}\boldsymbol{D} \cdot \boldsymbol{\sigma_{map}}) d\Omega \right] \tag{5.4}$$

where

c: light velocity,

$\boldsymbol{D}$, $\boldsymbol{\sigma D}$: True baseline vector and offset of the adopted baseline vector from the true baseline vector,

$\boldsymbol{\Delta s}(\boldsymbol{\nu})$: True radio source coordinate and offset of the adopted source coordinate from the true source coordinate,

ϕ^{LO}: Phase offset caused by the local frequency standard and the mixer,

τ^{inst}: Time-variable excess path delay caused by the electric transportation system (instrumental delay),

Δt: Time offset from the specific epoch,

τ^{atm}: Time-variable unknown excess path delay caused by the atmosphere towards the source,

$\phi^{\mathrm{IF}}(\nu)$: Phase residual derived by the complex bandpass response in the IF channel,

$2\pi n$: 2π-n radians ambiguity in the phase,

$\phi^{\mathrm{str}}(\nu)$: Phase offset caused by brightness distribution of the radio source, $B(\boldsymbol{\sigma_{map}}, \nu)$,

$\boldsymbol{\sigma_{map}}$: Position offset vector with respect to the specific celestial location, here equal to $\boldsymbol{\Delta s}(\boldsymbol{\nu})$.

At the final stage, we need only information on the target source, $B(\boldsymbol{\sigma_{map}}, \nu)$ and $\boldsymbol{\Delta s(\nu)}$. Note that a target source, especially a maser source has different brightness distributions and position offsets among frequency or line-of-sight velocity. In equation 5.3, a term including $\boldsymbol{\sigma D}$ is ignored if it is sufficiently small with respect to $\boldsymbol{\Delta s(\nu)}$. This situation, however, is not satisfied in high-precision differential astrometry between two sources separated by as large as one arc degree.

Error terms in the second line of the right side of equation 5.3 should be removed out by data calibration. τ^{inst} and $\sigma\nu^{\text{LO}}$ are usually called as "clock parameters"; major parts of them are derived from the frequency standards of VLBI stations. They are smooth functions of time and can be removed by fringe fitting (see section 6.5.2). ϕ^{IF} is expected to be stable in the whole observation or within several hours and can be removed by obtaining the visibilities of bright quasars after fringe fitting (see section 9.1). τ^{atm} is a function of time and varies rapidly within a coherence time. It is removed by both fringe fitting (see sections 6.5.2 and 11.2) and self-calibration (see chapter 7).

5.1 Observation schedule

To appropriately calibrate maser source data, calibrators should be appropriately observed. This means that an observation schedule should be prepared with taking into account strategy of data calibration. There are special notes on observations of maser sources as follows.

5.1.1 Fringe finders

Usually VLBI row data have big unknown clock parameters, clock offsets (residual delays) and clock rate offsets (residual delay rates) even if every clock of observation stations is being maintained by a hydrogen-maser frequency standard and a GPS time-keeping system. These offsets sometimes achieve up to $1\mu s$ and 100 mHz, respectively. Such offsets severely smear fringe signals and prevent the data from coherent integration for the whole observation.

Quasars suitable for finding fringes are selected as *fringe finders*. Their celestial coordinates shall be well measured and they shall be so bright that they are detected within a coherence time even in most severe situations expected in the observations. They are observed once or more for a coherence time or longer in the observation.

5.1.2 Clock parameter calibrators

Usually, fringe finders are far away from the target sources of the observation on the sky plane. In actual, residual delays and delay rates contain not only clock parameters but also delay and rate residuals due to the atmospheric excess path delays. Because the latter is different among the sources located at different antenna elevation, continuum calibrators should be as close to the target sources as possible.

When target sources are bright continuum sources, themselves become clock parameter calibrators. On the other hand, when target sources are maser sources, another continuum calibrators are necessary because the maser sources themselves, they have maser emission in quite limited frequency range, cannot be used to estimate (group) delay offsets. The calibrators should be scanned every 30-90 min. At higher frequency bands, shorter time interval ($\sim$30 min) is adopted.

5.1.3 Maser fringe finders

Frequency setups that specify the number of IF channels, the local frequencies and band widths of the IF channels, should be exactly set for maser source observations. Even only setting a wrong local frequency, some parts or all of maser emission with narrow line spectrum in the limited range of Doppler frequency is lost from the data. In particular, the Doppler frequency varies from one season to another due to the Earth's orbital motion and rotation.

This frequency shift is, of course, bigger at the higher frequency. The observer should carefully check at which frequency the target maser sources are detected at the observation epoch. To check it during the observation, a bright maser source which can be detected in the total-power spectrum in real-time is useful. Therefore, for example, each of the VERA station has a real-time digital correlator to perform such a check with total-power spectra just before a VLBI observation starts.

5.1.4   Phase/position-reference sources

If the target sources are too weak to be detected within a coherence time, continuum sources that are very close to the target sources are scanned every period shorter than the coherence time followed by the target sources. Such scans are performed by quickly nodding an antenna; the method is called as *antenna-fast-switching phase-referencing.* Fringe phases, delays and rates of the continuum sources are interpolated to those of the target sources. Such continuum sources are called as *phase-reference sources.*

If the phase-reference source is a quasar, this is also used as *position reference.* On the contrary, when a target source is bright enough to be detected and used for data calibration, a position-reference source with faint emission is mapped in the opposite manner of that mentioned above. This method is calledas *inverse phase-referencing.*

5.1.5   Bandpass calibrators

Each of IF channels has *complex bandpass response*, which derives bias in amplitudes and a small phase slope along frequency. Information on complex bandpass response is necessary only when imaging continuum sources with very high dynamic range or maser sources with very precise relative position accuracy (e.g. in position errors smaller than 1/100 of angular resolution). The bandpass calibration may have to taken into account when the VLBI system uses analog band filters. Even if using digital band filters such as the VERA system, a receiver may have non-flat bandpass response in wider bandwidths. In any case, at least bandpass amplitude response should be calibrated. To obtain the bandpass response, amplitudes and phases are well determined in the individual frequency channels. Therefore, extremely bright continuum calibrators should be observed.

5.2   Step-by-step calibration

VLBI data calibration with AIPS is a series of updates of the calibration table (`CL`), which contains the *complex gain factors* having amplitudes and phases. Because phases in the gain factors are interpolated along frequency and time, they also have group delay residuals and phase drift rate residuals. Each of the `CL` table updates is made with the task `CLCAL` by applying solution `SN` tables to create a new `CL` table from an old `CL` table. Row visibility data are never transformed; the calibrated visibility data are created by applying the finest `CL` table to the row data. Therefore, disk spaces much larger than the size of row data are consumed rapidly.

5.3   Selecting a reference antenna

Every visibility plot and calibration in AIPS is fundamentally *antenna based*, and all telescope performance are evaluated with respect to the *reference antenna.* The reference antenna is chosen by a user with taking into account sensitivity and reliability in the performance. To obtain a larger number of calibration solutions with higher reliability, the reference antenna is a key in the data reduction.

There is another concern when choosing the reference antenna, baseline lengths. Generally speaking, an antenna close to the center of a VLBI array has an advantage to obtain a larger number of visibilities because, taking into account the Earth's rotation, this antenna observes radio sources with a larger number of the array antennas in the same observation period. In addition, a radio source has a finite angular size and visibility amplitude of the source is reduced roughly proportional to baseline length. Thus this antenna obtains visibilities with higher sensitivity.

5.4   Fringe search window

For maser data reduction, a user shall imagine a few types of the *fringe search windows* as shown in figure 5.1. In the fringe fitting described in fundamental calibration using continuum calibrators, a delay–rate window should be adopted, while frequency–rate window should be adopted in the maser data calibration.
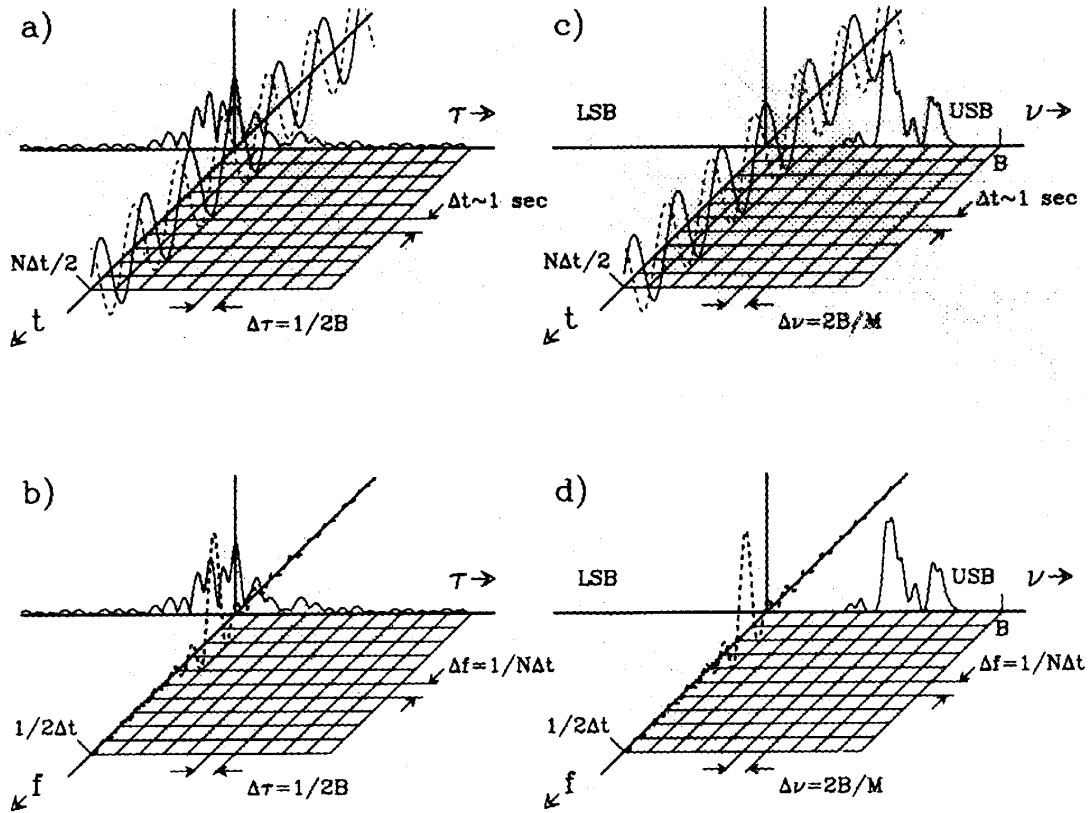
Figure 5.1: Fringe visibilities in fringe search windows. (a) search window in a time lag (τ) versus parameter period (t) plane; (b) same as (a) but in a time lag versus fringe frequency plane; (c) same as (a) but in a spectral frequency versus parameter period plane; (d) same as (a) but in a spectral frequency versus fringe frequency plane. For line sources, the obtained cross-power spectra have several spectral frequency peaks corresponding to the Doppler velocities of the line components in the planes (c) and (d), and have several fringe frequency peaks corresponding to the position offsets from the correlation center position in the planes (b) and (d). For continuum sources with flat power spectra, there are several time lag peaks in the planes (a) and (b). In the fringe search procedure, the planes (b) and (d) are used for the line and continuum sources, respectively. These figures are cited from Reid (1995).

5.5 Set a coherence time

A coherence time shall be taken into account when making observation schedules and when making data reduction. The coherence time can be estimated with the task COHER (see section 4.7).

Empirically, a coherence time described in famous books is slightly shorter than a period for which a visibility amplitude is reduced. Clock search described in chapter 6 can use the latter period. Therefore, scans of continuum calibrators are set to be slightly longer than the coherence time. On the other hand, phase-referencing and fringe fitting that are performed to interpolate phases between scans should adopt a solution interval (the adverb SOLINT) shorter than the coherence time. Otherwise, removal of 2π-n radians ambiguity may fail.

Chapter 6

Fundamental calibration

Figure 6.1 describes a flow of the fundamental calibration in AIPS. Each of the calibration procedures are briefly described in the following sections.

6.1 Plotting calibration solution

Calibration tasks such as `ACCOR`, `APCAL`, `FRING CALIB` generate solution (`SN`) tables. The solution tables can be plotted with the task `SNPLT`. The calibration solutions in amplitude, phase, delay and rate are plotted against time by setting `OPTYPE='AMP'`, `'PHAS'`, `'DELA'` and `'RATE'`, respectively. When setting `DOTV=1`, the plot is displayed on the AIPS TV Server, while setting `DOTV=-1`, the plot is saved in plot (`PL`) files in the AIPS UV data. The `PL` files are printed out with the task `LWPLA` on a printer without specifying the adverb `OUTFILE` or plotted in PostScript files with specifying the adverb `OUTFILE`.

6.2 Applying calibration

As described in section 6.2, data calibration is a series of updating the calibration (`CL`) table. The task `CLCAL` makes updating a `CL` table. The following is an example of `CLCAL` inputs. A `CL` table that is newly created can be applied several `SN` tables at the same time. The `CL` table can be applied many times without removing previous application. Therefore, when previous applications were wrong, the `CL` is recommended to be deleted.

Here some of important adverbs in `CLCAL` are described in detail.

6.2.1 SOURCE

It specifies sources whose visibilities are calibrated. In most cases, all sources can be selected (`SOURCE=' '`).

6.2.2 CALSOUR

It specifies sources whose solutions in the specific calibration task is applied. Combination of `SOURCE` and `CALSOUR` can change for the same `CL` table. This is convenient when the AIPS UV data several pairs of target-reference sources in antenna-fast-switching phase-referencing, which are specified in `SOURCE` and `CALSOUR`, respectively. In this case, only scans of sources that specified in the latter adverb are passed in `CLCAL` without incorrect data interpolation to other sources.

6.2.3 INTREPOL

It controls methods to interpolate calibration solutions provided by `SN` tables. If calibration solutions provided have time intervals short enough to avoid any ambiguity in the interpolation, the default `INTERPOL='2PT'` can be adopted. In the antenna-fast-switching phase-referencing, `INTERPOL='AMBG'` is recommended to use delay rate solutions and to avoid 2π-n radians ambiguity in phase interpolation. If calibration solutions
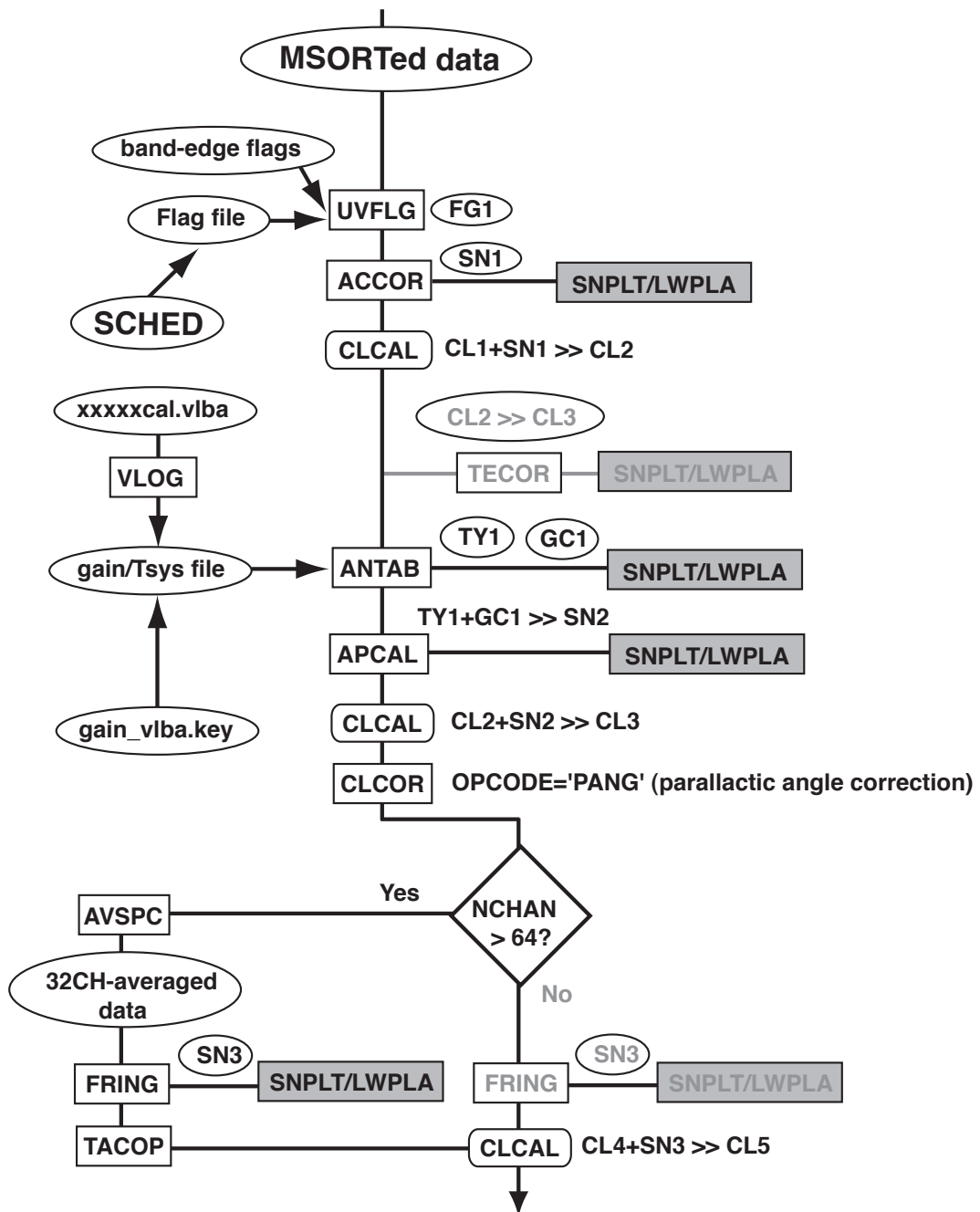
Figure 6.1: Flow chart of the part that describes fundamental calibration.

are temporarily sparse, in the case of amplitude calibration on basis of sparse data set of system noise temperature, other interpolation methods may be adopted.

6.2.4 CUTOFF

The default (`CUTOFF=0`) means that all data points in the `CL` table are interpolated with the applied `SN` table. Sometimes this default affects the calibration result. If calibration solutions in a specific time range were not obtained because of some bad reason, the data at this time range should be flagged out. When setting this adverb in unit of minute, an epoch without any calibration solution within this adverb criterion from the epoch is filtered.

6.3 Sampling bias correction

From this point, the flow of the fundamental calibration is described.

The task `ACCOR` makes this correction, which is described in other text in more detail. Because sampling bias usually occurs stably, a solution interval (`SOLINT`) is set relatively to a long period (10–60 min).

6.4 Amplitude calibration

6.4.1 Making gain and system temperature tables

To make amplitude calibration, information on gains and system noise temperatures of antennas are necessary in a proper format for the AIPS task `ANTAB` to read them and to create a gain curve (`GC`) and system noise temperature (`TY`) tables.

For VLBA data, these information is contained in the file named *[project code]*`cal.vlba` and put on the host *aspen* (accessible from the VLBA web page). The file is extracted by using the task `VLOG`. To obtain antenna gain information, the file `vlba_gain.key` is also necessary. This shall be attached in the `cal.vlba` data mentioned above or the system noise temperature data named *[project code]*.`TSYS`.

For other telescopes, a gain file should be prepared with a format shown as follows.

```
! JNET_gain.txt: gains for J-Net telescopes
!
GAIN NOBEYA45 ALTAZ   DPFU =  0.362 FREQ=21530, 22630 POLY=  1.000 /
GAIN KASHIM34 ALTAZ   DPFU =  0.115 FREQ=21530, 22630 POLY=  1.000 /
GAIN MIZNAO10 ALTAZ   DPFU =  0.010 FREQ=21530, 22630 POLY=  1.000 /
GAIN KAGOSIMA ALTAZ   DPFU =  0.005 FREQ=21530, 22630 POLY=  1.000 /
GAIN MIZNAO20 ALTAZ   DPFU =  0.057 FREQ=21530, 22630 POLY=  1.000 /
GAIN IRIKI    ALTAZ   DPFU =  0.061 FREQ=21530, 22630 POLY=  1.000 /
GAIN OGASA20  ALTAZ   DPFU =  0.051 FREQ=21530, 22630 POLY=  1.000 /
GAIN ISHIGAKI ALTAZ   DPFU =  0.048 FREQ=21530, 22630 POLY=  1.000 /
!
```

where `GAIN` declares the gain information of the antenna specified after this string, `DPFU` is the *degree per flux density*, `FREQ` specifies the frequency range (bottom and top) in which the gain information is valid.

Files of system noise temperatures also should be prepared with a format shown as follows.

```
!--- Tsys data ----------
!
TSYS IRIKI    INDEX='L1' FT = 1.0 TIMEOFF=0 /
357 17:33.1   224.1
357 18:06.3   246.8
357 18:56.8   206.3
/
!
TSYS OGASA20  INDEX='L1' FT = 1.0 TIMEOFF=0 /
357 17:33.1   209.4
```

```
357 18:06.3   249.1
357 18:56.8   214.3
/
!
TSYS ISHIGAKI INDEX='L1' FT = 1.0 TIMEOFF=0 /
357 17:33.1   442.6
357 18:06.3   369.7
357 18:56.8   386.2
/
!
TSYS KASHIM34 INDEX='L1' FT = 1.0 TIMEOFF=0 /
357 17:35.0   131.3
357 18:55.0   140.1
/
```

where `TSYS` declares the gain information of the antenna specified after this string, `INDEX` describes a format for an array of circular polarization and IF channels. Here, `L1` means IF1 Left circular polarization. When having left and right circular polarization in each of four IF channels, `INDEX` is describes as follows, `INDEX='L1' ,'R1','L2','R2','L3','R3','L4','R4'`. To understand the description in more detail, type `EXPLAIN ANTAB`.

6.4.2   Creating amplitude calibration solution

Using the gain (`GC`) and system noise temperature (`TY`) tables created in the task `ANTAB`, a new solution (`SN`) table is created by the task `APCAL`. The performance of the task `APCAL` is described in other texts.

6.4.3   Parallactic angle correction

Some of recent VLBI systems are able to receive both of left-hand right-hand circular polarization signals at the same time. Not only in such system but also the systems using azimuth-elevation mount antennas, leakage of another circular polarization component should be taken into account. The leakage varies with parallactic angle of the receiver (rotation angle of the receiver with respect to the radio source) and affects visibilities, especially in VLBI polarimetry. The *parallactic angle correction* can be made in the task `CLCOR` by seting the adverb `OPTYPE='PANG'`. This task modifies the specified `CL` table. It is appropriate to perform this correction before fringe fitting and further data calibration.

6.5   Fringe fitting

At this stage, only continuum calibrators are used in the fringe fitting to solve clock parameters varying on a time scale of about one hour. In the solutions, average excess path delays due to the atmosphere towards the sky close to the target (maser) sources are also included.

6.5.1   Averaging spectral channels

Usually VLBI data observing maser sources have a large number of spectral channels. For fringe fitting, 16–64 spectral channels are sufficient and suitable for saving calculation time. The task `AVSPC` creates a channel-averaged data. In the task, the adverb `AVOPTION='SUBS'` is specified to average the spectral channels. The adverb `CHANNEL` is the number of spectral channels averaged into one channel. For example, from data having 512 spectral channels, new data having 32 spectral channels are created when `CHANNEL=16`. At that time, flagging is also performed with an existing flag (`FG`) table.

6.5.2   Fundamental fringe fitting

The task `FRING` performs fringe fitting as mentioned above. At this stage, scans of only continuum calibrators are used. Fringe fitting using scans of maser emission is described in the section 11.2.
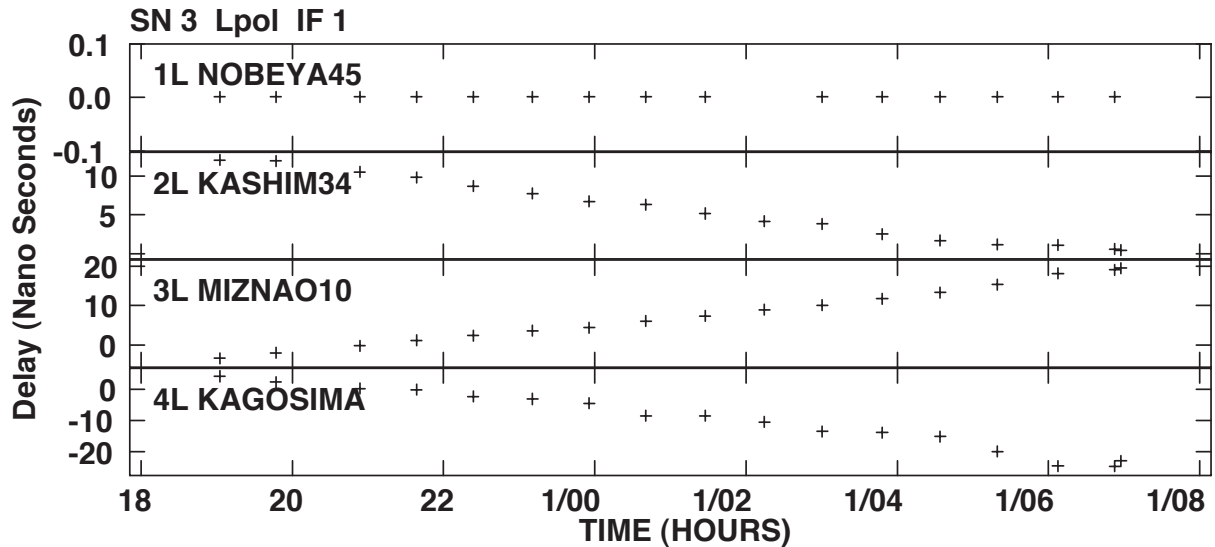
Figure 6.2: Clock offsets revealed in the fundamental fringe fitting with the task FRING. The calibrator JVAS0212+735 was observed at the 22.2 GHz band every 40 minutes. Because Nobeyama 45-m telescope is a reference antenna, delays of this telescope are always zero.

```
TASK  'FRING'       Calling the task FRING.
INDISK 1; GETN 100  Calling UV file in the AIPS catalog file.
CALSOUR 'NRAO530' '0212+735'    Calibrator sources
BCHAN  1     Lowest channel number 0=>all
ECHAN  0     Highest channel number
DOCALIB  2   Performing calibration with a CL table and weights.
GAINUSE  3   CL table to be applied.
FLAGVER  0   Latest FG table is applied.
DOBAND=-1    Bandpass (BP) table has not yet been created.
REFANT  1    Reference antenna.
SEARCH  2 0  Second priority antenna when without the reference antenna.
SOLINT  3    Solution interval, a little longer than a coherence time.
APARM    0   Clear APARM.
APARM(7) 7   Signal-to-noise ratio cutoff.
APARM(9) 1   Second priority antenna is used when without the reference antenna.
DPARM(1) 0   3 baseline combinations to make closures.
DPARM(2) 0; DPARM(3) 0  Fringe search window is automatically set.
DPARM(4) 2   Parameter period in the correlation in second.
SNVER    0   A new SN table is created.
INP; GO
```

At this stage, it is better to adopt a longer integration duration (solution period) to obtain mainly group delays (clock offsets) with higher signal-to-noise ratios. Even if fringe phases are rapidly fluctuated on a shorter time scale than a coherence time, group delays are more stable on a longer time scale within their estimation uncertainty (1-3 nsec).

For example, suppose an uncertainty in the estimated clock offset (group delay error) $\sigma\tau^{\mathrm{inst}}$ that derives a phase drift along frequency. At the frequency ν separated by $\Delta\nu$ from a reference frequency, a phase error $\sigma\phi$ is expected as follow,

$$\sigma\phi = \Delta\nu\sigma\tau^{\mathrm{inst}} \sim \nu\frac{\boldsymbol{D}\cdot\boldsymbol{\sigma s}}{c}, \tag{6.1}$$

$$\sigma s \sim \frac{c}{D} \frac{\Delta \nu}{\nu} \sigma\tau^{\mathrm{inst}}. \tag{6.2}$$

By inserting, for example, $D = 1000$ km, $c = 3 \times 10^5$ km s^{-1} and $\Delta\nu/\nu = 1/1000$, an uncertainty of the instrumental delay $\sigma\tau^{\mathrm{inst}} = 3$ nsec derives a relative position error $\sigma s \sim 180$ μas.

On the other hand, phase fluctuation on a shorter time scale can be compensated in the *self-calibration* procedures described in the next chapter. At this stage only large phase drifts on a longer time scale are compensated for removing 2π-n radians ambiguity in phase connection between successive short epochs.

Chapter 7

Self-calibration and hybrid mapping

The detail of the self-calibration and hybrid mapping is described in other books (e.g. [5]). Here concentrates on how they are performed in AIPS. Figure 7.1 shows a flow to perform the self-calibration and hybrid mapping. Definition of *self-calibration* and *hybrid-mapping* are different among the text books, here the hybrid-mapping is defined as the whole procedures to obtain a CLEAN map and the self-calibration is defined as the procedure to obtain complex gain factors based on an assumed source model.

7.1 Making a source image

The first step of the hybrid mapping is to provide a source brightness model. It is still fine to assume a simple model (for example, one point Gaussian distribution). It is sometimes necessary to provide the model on basis of the brightness distribution that is actually observed.

7.1.1 Dirty beam, dirty map and CLEAN map

A dirty beam is the VLBI synthesized beam that is directly calculated with (u, v) distribution and weights of visibilities by inverse Fourier transformation. A dirty map is the map that is obtained by inverse Fourier transformation of the visibilities without any CLEAN process. A dirty map is useful to judge the detection and existence of a radio source or true peak components in the brightness distribution. The dirty map is composed of a true source brightness distribution convolved by the dirty beam. A CLEAN map is the map obtained after deconvolution of the dirty image by the dirty beam in an iterative process (see, e.g., [5]).

7.1.2 Split a single source file from a multi-source UV data

It is convenient to split visibility data only of the target source from the original (multi-source) UV data. The task SPLIT creates a new single-source file as follows.

```
INNAME     'SPLIT'          Call the task SPLIT.
INDISK 1; GETN 100          Get the original (multi-source) UV data.
SOURCES    'LKHA234' ' '    Target source split.
STOKES     ' '              All Stokes types of data are passed.
BIF 1; EIF 0                All IF data are passed.
BCHAN 1; ECHAN 0            All channels are passed (except for the band edges).
DOCALIB      2              Apply a CL table and weights.
GAINUSE      9              CL table version to be applied.
FLAGVER      1              Flag table version (including band edge flags).
DOBAND       1              Apply bandpass (BP) table.
BPVER        1              BP table version to be applied.
OUTDISK      1              Output UV file disk unit number.
OUTCLASS 'SPLIT '           Specifies the class name of the output single-source file.
OUTSEQ       0              A new sequence number is specified for the output file.
DOUVCOMP     1              Compressed data are output.
```
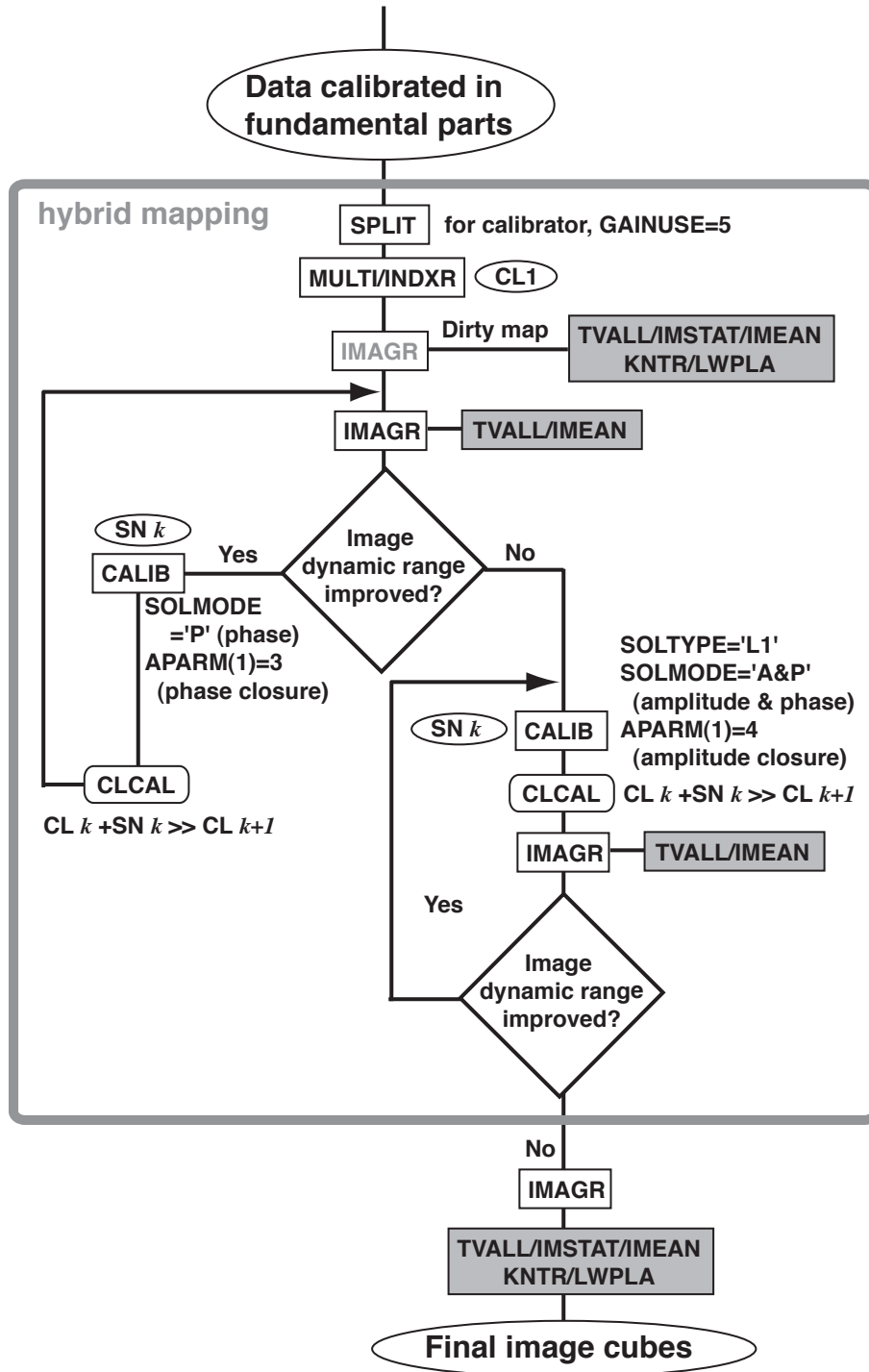
Figure 7.1: Flow chart of the part that describes the hybrid mapping.

```
APARM 2 2 0                      Averaging spectral channels but having multi-IF channels.
INP; GO
```

To create `CL` tables in the following self-calibration process, the tasks `MULTI` (to create a new multi-source file) and `INDXR` (to create a new `NX` table) shall be performed.

7.1.3   Making a dirty beam and a dirty map

The task `IMAGR` creates a source image as well as a dirty beam. An example of adverb setting in the task `IMAGR` is shown as follows.

```
TASK 'IMAGR'           Call the task 'IMAGR'.
INDISK 1; GENT 101     Get a SPLITed file.
SOURCES 'LKHA234' ' '  Source name made its images.
DOCALIB  2             Calibrate visibilities with a CL table and weights.
GAINUSE  2             CL table to be applied.
FLAGVER=-1; DOBAND=-1  No FG and BP tables are applied.
STOKES    'I'          Stokes parameter I (intensity) map is created.
BCHAN 0; ECHAN 0       All channels are selected.
NCHAV 1; CHINC 1       It is unnecessary to average and skip spectral channels.
BIF 1; EIF 0           Select all IF channels.
OUTNAME   'LKHA'       Output image name (name).
OUTDISK      1         Output image disk drive #.
OUTSEQ       1         Output seq. no.
OUTVER       1         Version number of the CC table.
CLR2N     Clear IN2DISK, IN2NAME, IN2CLASS, IN2SEQ.
CELLSIZE  .0002 .0002  (X,Y) grid size in arcsecond, smaller than 1/4 of the synthesized beam.
IMSIZE 512  512        Minimum image size
NFIELD       1         Only one field is selected.
FLDSIZE 512 512        Clean size of each field.
RASHIFT 0; DECSHIFT 0  No position shift of the field.
UVWTFN    'NA'         Natural weight is specified at first.
NITER     0            No iteration because of making a dirty map.
DOTV=1                 Display residuals on TV for interactive CLEAN control.
INP; GO
```

7.1.4   Controlling AIPS TV Server

The obtained image is shown on the AIPS TV Server with the verbs, `TVAL` (for single frequency channel) or `TVMOVIE` (for multiple channels). The verb `TVCLEAR` clears one of the screen channels of the TV server. More simply, the task `TVINIT` clears all of the items displayed on the TV server. `TVLABEL` gives lavels (coordinate information) for the image displayed on the TV server.

7.2   Iterative process in hybrid mapping and self-calibration

In the hybrid mapping, at the first step, a user should provide a source model created from a simple assumption of a source brightness distribution (one-point Gaussian distribution at the map origin) or from a rough image obtained by CLEANmapping. Such a source model is set in the task `CALIB`. The task `CALIB` outputs a new solution (`SN`) table. Then a new CLEAN image with better quality is obtained from the visibilities calibrated by this `SN` table in the task `IMAGR`. A CLEAN image newly obtained is again used as a better source brightness model in the task `CALIB`. Thus the hybrid mapping is an iterative process followed by the tasks `IMAGE`, `CALIB` and `CLCAL` If a single source file, or an output of the task `SPLIT` is used in this process, only `SN` tables are directly used in the task `IMAGR` (without applying the task `CLCAL`).
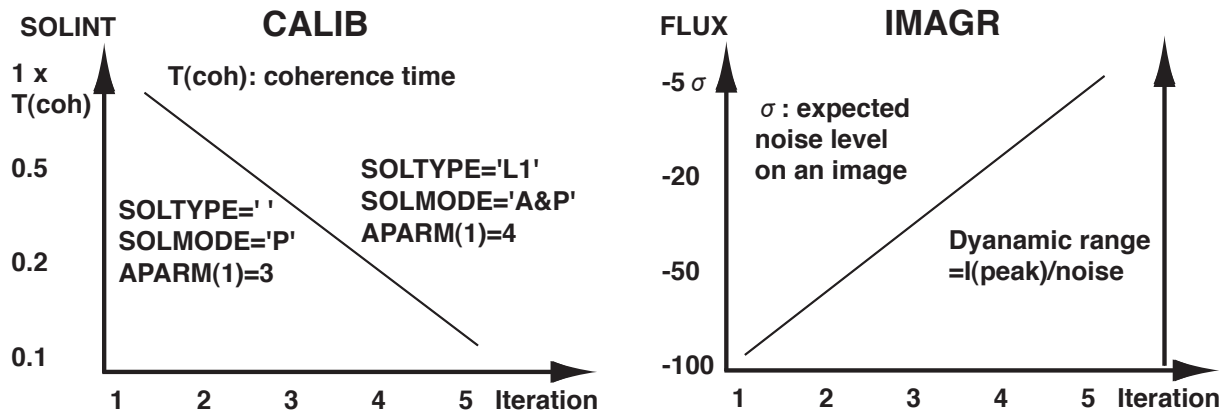
Figure 7.2: Variation of SOLINT, FLUX and other adverbs with iterations in the tasks CALIB (*left*) and IMAGR (*right*).

7.2.1 Selfcalibration

An example of adverb setting in the task CALIB is shown as follows.

```
TASK 'CALIB'            Call the task CALIB.
INDISK 1; GETN 101      Get SPLITed file.
CALSOUR 'LKHA234' ''    Calibrator sources.
BCHAN 0; ECHAN 0        Select all spectral channels.
ANTENNAS      0         Select all antennas.
ANTUSE        2 0       Mean gain is calculated with antenna # 2.
UVRANGE       0         Set all uv range for weight, useful for extended sources.
DOCALIB       2         Calibrate data with a CL table and weights.
GAINUSE       4         CL table to be applied.
FLAGVER=-1; DOBAND=-1   No FG and BP tables applied.
IN2DISK 1; GET2N 102    Get an image file that was created in the task IMAGR.
INVERS    1             CC file version # in the image file.
NCOMP      20           Number of CLEAN comps to be used for source model.
OUTNAME    'LkHa234     Output UV file name (name).
OUTCLASS   'CALIB'      Output UV file name (class).
OUTSEQ        0         A new sequence number is assigned.
OUTDISK       1         Output UV file disk drive #.
REFANT        2         Reference antenna.
SOLINT        0.5       Solution interval in minute.
APARM(1)=3  3 and 4 ants make closures in pha. and amp./pha. calibrations, respectively.
APARM(7)      7         Signal-to-noise ratio cutoff.
SOLTYPE    'L1'         'L1' should be selected in amplitude/phase calibration.
SOLMODE    'A&P'        Either 'P' (phase only ) or  'A&P' (amplitude/phase) is selected.
SNVER         0         A new SN table is generated.
INP; GO
```

If a multi-source file is used, the obtained SN table should be applied to the existing CL table with the task CLCAL.

7.2.2 Making a CLEANed image

In making a CLEAN image with the task IMAGR, the following adverbs control the CLEAN performance.

```
NITER 1000  Number of CLEAN components picked up in maximum, or number of iterations.
```

```
NMAP  1      Number of maps containing the radio source emission.
CLBOX 0      No pixel coordinate of CLEAN boxes is specified for interactive setting.
GAIN  0.05   Clean loop gain (0.01-0.2).
FLUX=-0.2    CLEAN stops when a Clean comp. is weaker than 0.2 Jy or has a negative value.
```

The coordinates of *CLEAN boxes* in which CLEAN components are picked up are interactively set on the AIPS TV Server. Afterward, the adverbs `CLBOX` is set in the iterative process in the hybrid mapping in which a user knows where CLEAN components are expected to exist.

7.2.3 Checking image statistics

(1) The verb `TVBOX` let a user put boxes on the image displayed on the AIPS TV Server. When quitting the verb, pixel coordinates at bottom left and top right corners of the boxes are displayed. These coordinates will be used in the image statistics.

(2) The task `IMEAM` displays results of the image statistics in a selected field, maximum and minimum intensities and the pixels providing these values, mean and r.m.s. levels of intensities. The statistic field is selected by the verb `TVBOX` and specified in the adverbs `BLC` (bottom left corner) and `TRC` (top right corner).

(3) The verb `IMSTAT` returns results of the image statistics in the specific adverbs.

(4) The task `PRTCC` prints a list of CLEAN components of the specified image (or image cube).

7.2.4 End of iteration process

The hybrid-mapping and self-calibration is an iterative process in which calibration solutions with the better solutions and higher time resolution are gradually obtained from the better source brightness model. In the imaging (the task `IMAGR`), the adverb `FLUX` controls the quality of an obtained image, set to be larger absolute value to smaller absolute value. The value of the adverb reaches 3-5 times as big as a noise level calculated with noise theory and observation parameters. This control is meaningful when iterations of self-calibration improve the calibrated data.

The quality of the self-calibration solutions are controlled by the adverb `SOLINT`, `SOLMODE` in the task `CALIB`. The value of the adverb `SOLINT` is set from longer (but shorter than a coherence time) to shorter (equal to a parameter period if possible). The parameter of the adverb `SOLMODE` is set to 'P' at the beginning and to 'A&P' in the final iteration stage. Variation in the adverbs values mentioned above is presented in figure 7.2.

Result of every step of the iterations should be check using the tasks and verbs listed in section 7.2.3. The *dynamic range* on an image, a peak intensity divided by r.m.s noise intensity, should be improved by the iterations. If the improvement is saturated, then the iteration process stops.

Chapter 8

Strategy on observation and calibration (2)

This chapter describes the importance of visibility calibration by watching every spectral channels especially for spectral line or maser source data. Different from images of continuum emission sources, the maser sources consist of a number of maser spots that have different locations and line-of-sight velocities. This means that it is essential to make excess path delay calibration and amplitude calibration for individual spectral channels. There are several difference in planning observations between for continuum and maser sources. Here such differences are mainly discussed.

8.1 Group delay estimation

Because a maser source have emission in the limited number of spectral channels, even within which fringe phases are quite different, group delays or clock offsets cannot be estimated with the maser emission. Therefore, another continuum calibrators are necessary to make clock offset calibration (see also section 5.1.2). Note that usually the continuum calibrators are far away from the target maser source and that excess path delays due to the atmosphere varies mainly with antenna elevation. Therefore, an accuracy of the group-delay estimation towards the maser source is limited by the angular separation between the target and the calibrators.

8.2 Bandpass calibration

To make maser astrometry with high precision or to get continuum source images with extremely high dynamic range image, bandpass calibration, especially for bandpass phase calibration, should be made using very bright continuum calibrators (see also section 5.1.5). The data shall not be averaged along frequency except for data having extremely high spectral resolution. At frequency bands of 22 GHz or higher, it is quit difficult to get the bandpass phase response unless sufficient time is consumed to scan the bright continuum calibrators. For example, at 22 GHz including H_2O astronomical maser emission, only 10 or less continuum calibrators can be used for this purpose. These calibrators still need big telescopes such as Nobeyama 45-m telescopes. According to the author's experience, such calibrators are scanned for as long as 40 minutes in Japanese VLBI Network (J-Net) observations. It is lucky if such bright calibrators can be used for clock offset calibration; in this case no extra time is necessary only for getting bandpass phase characteristics.

For these reasons, digital sampling just after down-converting the radio frequency signals and digital filtering for base band channel data are essential. VERA has already introduced these systems, but the obtained data are not free from bandpass response problem because receivers and low-noise amplifiers still have the bandpass responses in wide frequency widths.

8.3   Velocity tracking

Suppose that individual maser spots having specific line-of-sight velocities with respect to the standard frame (e.g., the local stand of rest) generate maser emission at different Doppler frequencies from time to another because of the Earth's orbiting motion and rotation. A velocity vector of the Earth with respect to the target maser source varies by up to 1 km s^{-1}and 0.4 km s^{-1}per day due to them, respectively (see also, e.g., [19, 18]). Such velocity drifts are bigger than a velocity spacing of a spectral channel of VLBI data (typically 0.2 km s^{-1}). In the maser data analysis, visibilities contained in the *same Doppler velocity* should be collected in a *velocity* channel. Alternatively, fringe phases should be shifted as described in the texts ([19, 18]).

8.4   Amplitude calibration with maser emission

Amplitude calibration described in the previous chapter is imperfect even if precise data of system noise temperatures and antenna gains are provided. It is because the procedures mentioned above does not trace the performance of antenna pointing. In the bigger telescopes with smaller beams, antenna pointing is affected by wind, sun light and weather condition. The observed flux density of the sources rapidly changes with time. When a maser source is bright enough to be detected within a short period ($\leq$ 1 min) and its size of maser feature distribution is compact (within several arcseconds), this can be used as an amplitude calibrator. This method is called as the *template method*.

In the template method, a "template" total-power spectrum is prepared from a telescope having good sensitivity at an epoch when antenna parameters (gain and system noise temperature) are known. The amplitude of the template spectrum is compared with those taken from other telescopes and at other epochs.

The relative accuracy of the amplitude calibration achieves a few percents. However, this method is invalid when the maser source is variable during the observation (sometimes the flux variation occurs). We have a limited number of chances to perform the template method because we need bright maser emission (over 100 Jy) that can be detected with every telescope for a short period.

Chapter 9

Advanced calibration

This chapter describes further data calibration for obtaining maser image cubes (and high quality continuum images). Figure 9.1 presents a flow of the advanced calibration, from the data that are calibrated in the fundamental procedures described in previous chapters to making the data which can be used for creating the final image cubes.

9.1 Bandpass response

The task `BPASS` calculates bandpass response and creates a bandpass (`BP`) table. The performance of the task `BPASS` is described in other texts. When setting the adverb `BPASSPRM=1`, bandpass amplitude response is obtained from total-power spectra. There several notices in data reduction for maser sources especially when obtaining complex bandpass response.

- A solution interval (`SOLINT`) is set to be longer than duration of the whole observation time for obtaining (time-constant) complex bandpass response with sufficient quality.

- Fringe fitting and calibration should be completed before performing the task `BPASS`.

- Calibration for complex bandpass response is effective when phase slopes of the response are well found.

- If quality of the obtained response is poor, the solution should be smoothed among frequency channels.

An example of the complex bandpass response is presented in figure 9.2. The phase slopes are quite smooth and amplitude of the phase variation is smaller than 10 degrees except for the band edges. Thus complex bandpass response is useful when the maser emission has a wide frequency (velocity) coverage.

9.2 Doppler tracking

Because a single narrow maser component detected is apparently moving along frequency during the observation as the Earth orbits the Sun and daily rotates. Calibration of visibilities for such Earth's motion is called as *Doppler tracking*. The principle of the Doppler tracking is described in the text ([19, 18]). In AIPS all visibilities having the same line-of-sight velocity are collected in the same *velocity channel* after the Doppler tracking.

9.2.1 Defining the source velocities

In the original FITS file and AIPS UV data, no velocity information is specified for sources. But a user knows the correspondence between a Doppler frequency and a line-of-sight velocity of the maser source. In more convenient cases, especially when using NRAO's SCHED for making an observation schedule, the user know that a center channel of each IF channel exactly corresponds to a source velocity specified in the SCHED keyin file. The AIPS task `SETJY` sets such correspondence in a source (`SU`) table as follows.
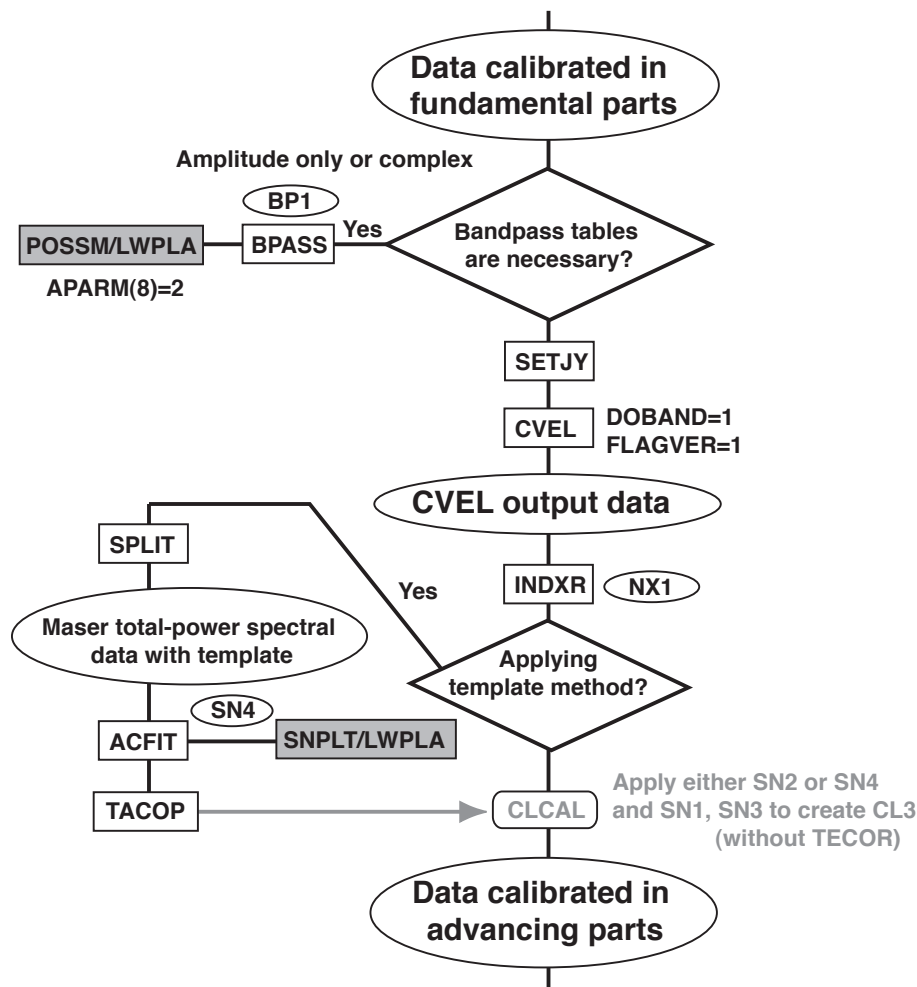
Figure 9.1: Flow chart of the part that describes the advanced data calibration.

```
TASK      'SETJY'      Call the task SETJY.
SOURCES   'LKHA234'    Sources to be modified.
BIF       1            Low IF # for flux density.
EIF       1            High IF # for flux density.
ZEROSP    0            Clear I,Q,U,V flux density.
OPTYPE    ' '          Clear function option type.
SYSVEL=-17.9           Velocity of the maser source (km/s).
RESTFREQ 2.223E+10, 5080000 Set a rest frequency of H2O maser emission (22,235,080,000 Hz).
VELTYP    'LSR'        Set a velocity type to be "local standar of rest".
VELDEF    'RADIO'      Means velocity definition in "radio astromony frame".
APARM     127 0        New channel pixel to which SYSVEL referes.
INP; GO
```

Note that the task SETJY should be used for each of IF channels to set different velocities for the IF channels covering different velocities. The contents of the modification for the SU table is confirmed in the task LISTR (see section 4.2).

9.2.2   Converting visibility data from in frequency to in velocity domain

The task CVEL performs not only Doppler velocity tracking by modifying visibilities but also changing the channel structure. In the output UV file of the task, frequency channels are converted to *velocity channels*.
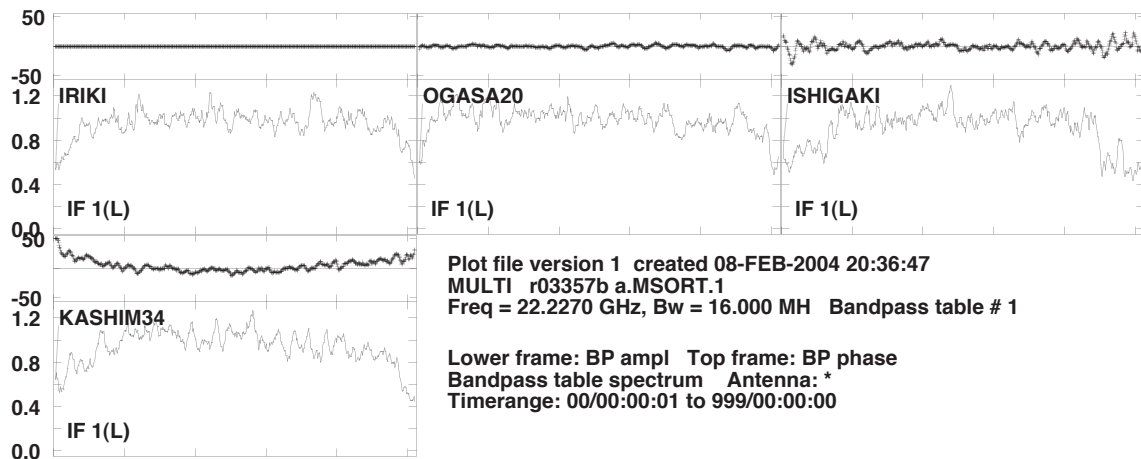
Figure 9.2: Bandpass characteristics obtained in `BPASS` and plotted with `POSSM` (`APARM(8)=2`). Only Kashima 34-m antenna has a slope of bandpass phase because an analogue base band filter (VSOP terminal) is used. Other VERA antennas have digital base band filters.

In the new channel system, a velocity channel specified in the adverb `APARM(1)` in the task `SETJY` has the velocity specified in the adverb `SYSVEL` in the same task. The task `CVEL` is controlled as follows.

```
TASK 'CVEL'              Call the task CVEL.
INDISK 1; GETN 100       Get a UV file.
OUTNAME    'j03153b'     Output UV file name (name)
OUTCLASS   'CVEL'        Output UV file name (class)
OUTSEQ     1             Output UV file name (seq. #)
OUTDISK    1             Output UV file disk unit #
SOURCES    'LKHA234'     Source list to be shifted.
TIMERANG   0             Specify all time range.
FLAGVER    0             Apply the newest flag tabl.
DOBAND     1             Apply the BP table before maser data calibration.
BPVER      1             Bandpass table version applied.
INP; GO
```

A user carefully check the `CVEL` result by watching messages shown in the message server while the task is running. With wrong combination of the adverbs `SYSVEL` and `APARM(1)`, large channel shifts occur and many visibilities at one of the band edges are lost. After finishing the task `CVEL`, the task `INDXR` should be executed to make a new index (`NX`) table.

9.3 Template method using maser emission

The template spectrum and total-power spectral data are provided by the task `SPLIT` by setting the adverb `APARM(5)=2`. The task `ACFIT` performs the template method. *AIPS COOK BOOK* chap. 9 describes this method in more detail. A user needs information on a sytem noise temperature and a *degree per flux density* ($DPFU = 2k/A_{\mathrm{eff}}$) of the telescope at the epoch, from which and when the template spectrum was taken.

Chapter 10

Watching maser emission

At this stage, *reference velocity channels* should be selected, which contain maser emission suitable for calibration of the maser data. Such maser emission has so compact that visibility phase changes not by the maser structure but only by phase fluctuation due to the atmosphere. At least brightness structure of the maser emission should be so simple that phase calibration is easy. Of course, the maser emission should be bright enough to calibrate the maser data with short calibration solution intervals. In practice, amplitude information is also important to perform the channel selection. Such channel selection is performed with the tasks POSSM, VPLOT and UVPLT. The usage of the tasks POSSM and VPLOT are explained in sections 4.5 and 4.6, respectively.

10.1   Amplitude variation along time

Because visibility phases are severely fluctuated by the atmosphere, it is risky to judge source brightness structure with these phases. Instead visibility amplitudes are used for the judgment. Figure 10.1 shows time variation of phases and amplitudes of the maser emission in the velocity reference channels. The temporary variation in the amplitudes indicate an extended maser structure. The selected velocity channels, however, are more suitable for the reference channels than others because they have highest flux densities.

10.2   Amplitude and phase variation along velocity

Cross-power spectra are also useful for judging source structure. Amplitude profiles of the spectra dramatically change with time. Individual amplitude peaks may correspond to individual maser features, which have different sizes and locations. Because cross-power flux density is affected by source size and by blend of multiple features in the same velocity channel, flux densities vary relatively among the amplitude peaks. Velocity channels having large flux densities, therefore, are suitable for the reference channels.

It is risky, however, to choose the velocity channel at the amplitude peak, in which another weaker components might exist and the source structure might be complicated. At this situation, slope of fringe phases are useful to judge the source structure. If the phases are constant among several of the successive velocity channels, the source structures in the velocity channels are almost same, which is expectable for a common simple structure. Usually it is better to choose the velocity channels located slightly away from the amplitude peak to pick up one maser feature.

10.3   Amplitude against u-v distance

Flux density against u–v distance is obtained with the task UVPLT. This diagram indicates a source size and structure. When the radio source is extended, the flux density rapidly drops with u–v distance.
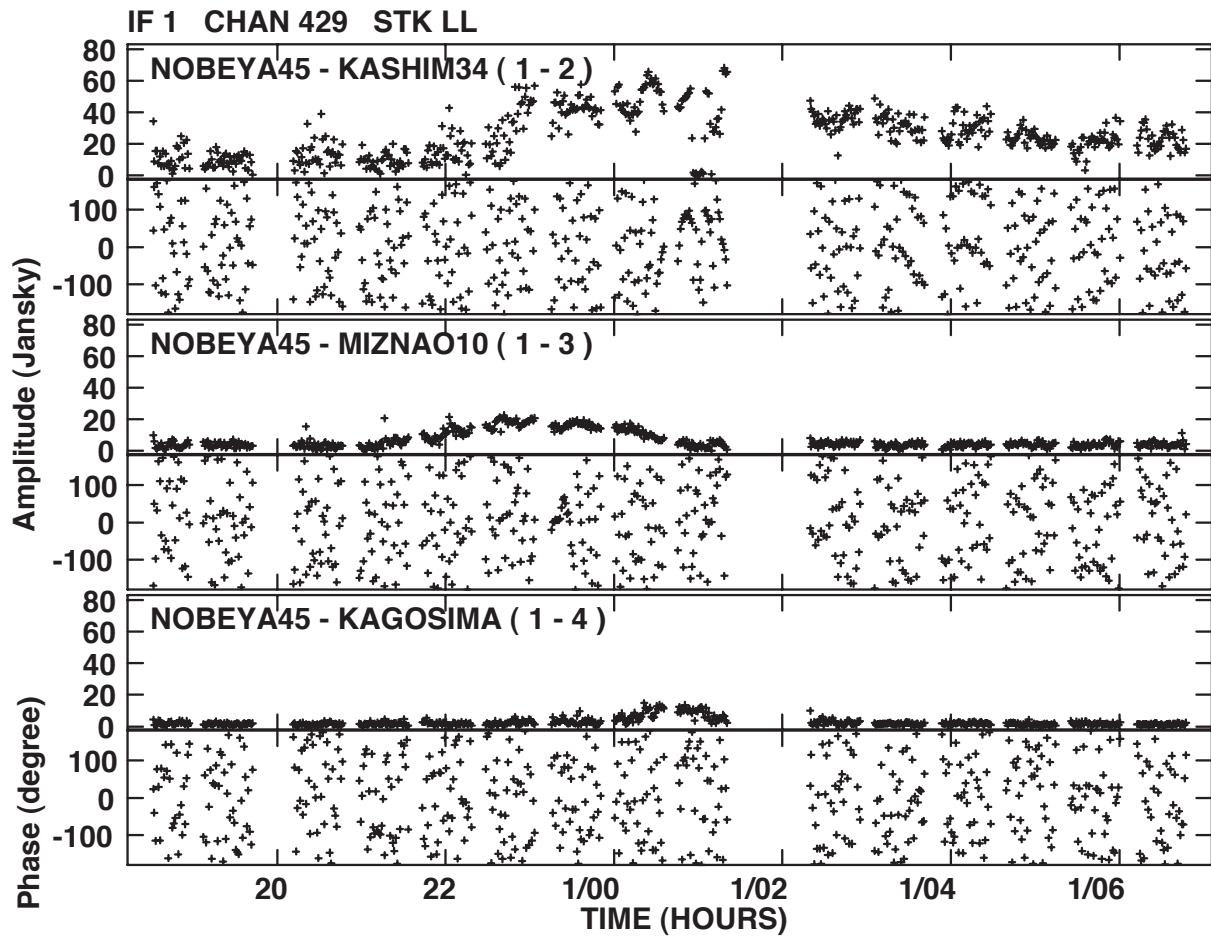
Figure 10.1: Temporary variation in visibility amplitudes and phases that is obtained with the task VPLOT. The reference channel candidates were selected in H$_2$O maser emission in LkHα234 observed with the J-Net. Fringe phase is still scattered because of the atmospheric phase fluctuation. On the other hand, visibility amplitudes exhibit systematic temporary variation. It is expected that the maser emission in this diagram so extended that the amplitudes increase only when projected baseline lengths shorten. The shortest baseline (Nobeyama-Kashima, 200 km) detected the highest flux density of the maser emission, which is consistent with the interpretation mentioned above.
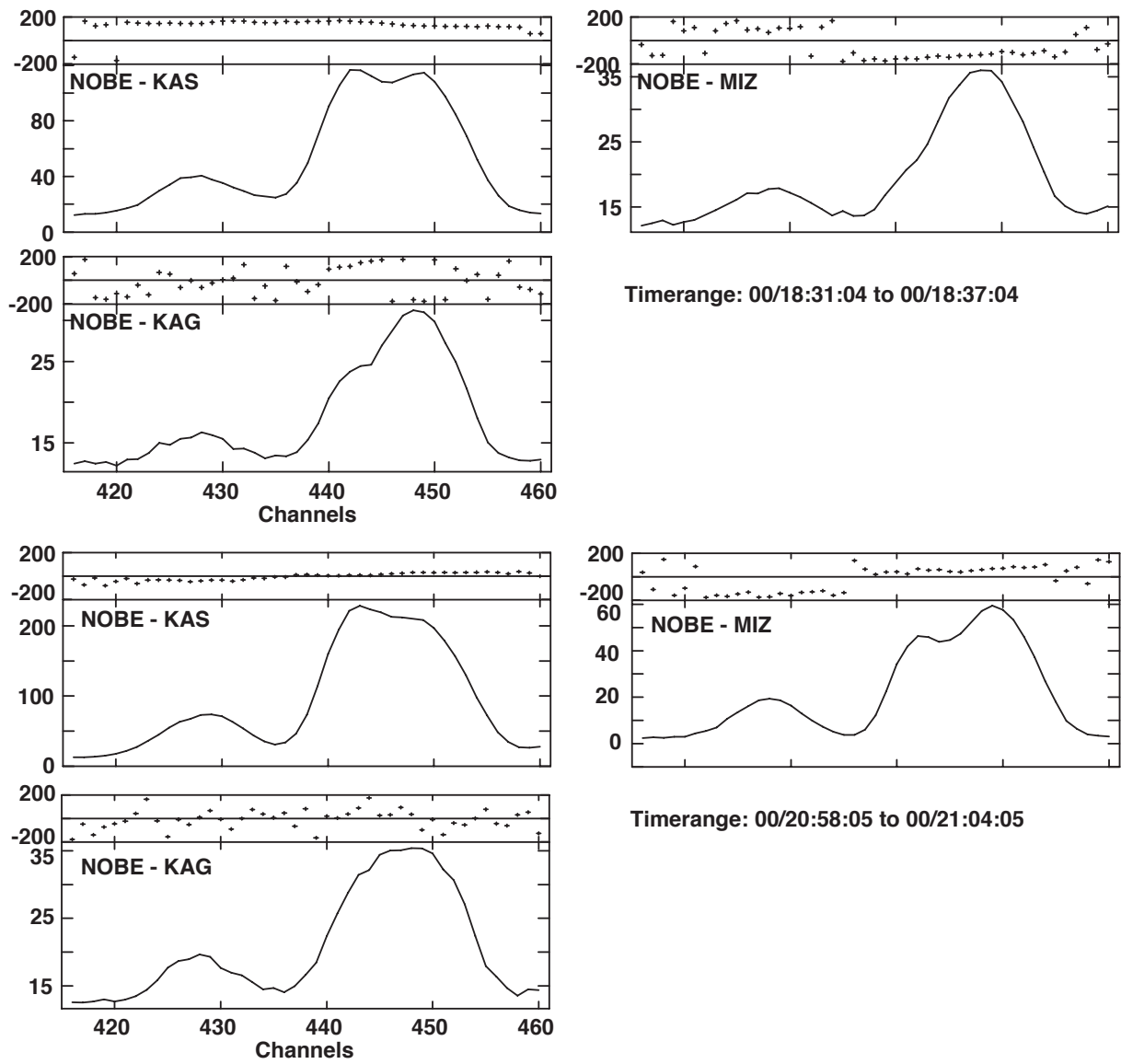
Figure 10.2: Variation of fringe amplitudes and phase along frequency, which are obtained from different baselines and epochs. There is an emission peak around the channel # 450, in which phase slope is flat and amplitudes are large and stable.

Chapter 11

Maser calibration

This chapter describes how maser source data are calibrated with the selected reference velocity channels, which is made in the previous chapter. The calibration solutions are applied to all of velocity channels and IF channels. Figure 11.1 shows a flow of the maser calibration.

11.1 Interactive data flagging

Previously, amplitude calibration and fringe fitting have used longer solution intervals that are close to a coherence time. In the self-calibration and fringe-fitting in antenna-fast-switching phase-referencing, shorter solution intervals shall be used. In such situations, bad data that usually appear in a short period ($\leq$60 sec) may generate strange calibration solutions and affect final images. Now such bad data should be removed *interactively*. Although some of tasks can automatically remove such bad data (e.g., CLIPM), interactive flagging is still recommended. The task IBLED make the interactive flagging.

It is expected that bad data appear in all velocity channels at the same time. It is convenient, therefore, to flag the bad data in the reference velocity channels then to apply the flag to all velocity channels. To perform it, at first, the reference velocity channels are split from the AIPS UV data by the task SPLIT. The SPLITed (single source) file is converted to be a multi-source file by the task MULTI, and a new NX table should be created by the task INDXR. This SPLITed file is used by IBLED to specify *all* velocity channels, or BCHAN=0; ECHAN=0. When a flag (FG) table newly created is copied to the original AIPS UV data, the flag information in the FG table can be applied to all velocity channels.

The author has flagged visibilities in Stokes parameter I in *all baseline data* in the task IBLED for VLBA, EVN and J-Net data. Visibility data in the task IBLED are averaged in a period shorter than a coherence time but the period is still long enough to have sufficient signal-to-noise ratios ($\geq$20).

11.2 Fringe fitting using maser data

At this stage, only residual delay rates and phases are calculated with the reference velocity channels by the task FRING. To perform it, the adverb DPARM(2)=-1 is specified to switch delay calculation off. The adverb SOLINT is still set to be a duration close to a coherence time. Note that BIF and EIF are never specified to keep the same number of IF channels in the SN table newly created as that in the AIPS UV data. Only the IF channel containing the reference velocity channels, of course, has good solution.

The solutions are displayed by the task SNPLT and by specifying OPTYPE='rate'. It is recommended to check whether the uncertainty of the rate solutions is within the value that can solve 2π-n radians ambiguity in phase connection. The fringe rate criterion $\sigma\nu_f$ in unit of Hz is calculated as follow,

$$\sigma\nu_f \leq \frac{1}{5\Delta T}, \tag{11.1}$$

where ΔT is the solution interval of the fringe fitting in unit of second. This equation means that a phase drift less than 1/5 rotation is permitted.
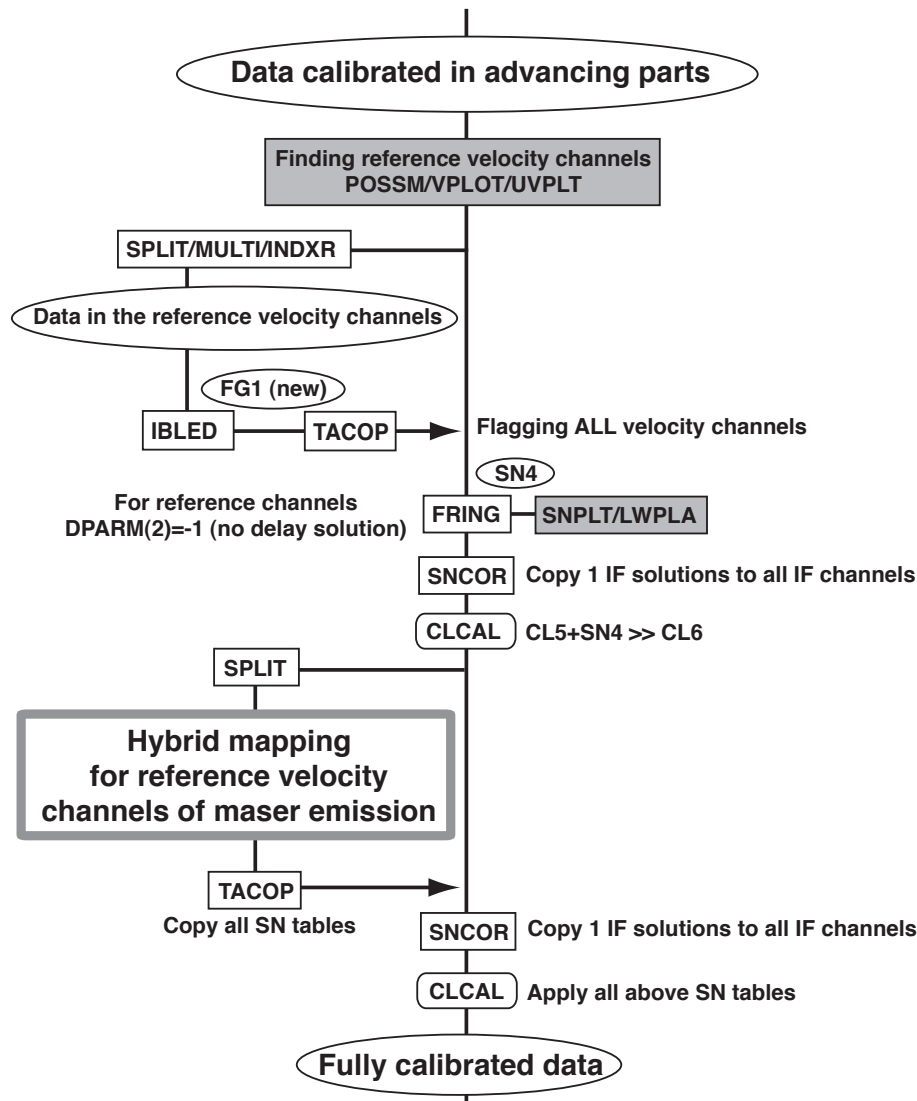
Figure 11.1: Flow chart of the part that describes calibration using reference velocity channels in maser emission data.

11.3 Edit `SN` tables

If there are solutions poorly determined in the `SN` table, they can be flagged out interactively by the task `SNEDT` on the AIPS TV Server. In particular, fringe fitting solutions should be carefully taken care because bad solutions may introduce 2π-n radians ambiguity in phase interpolation.

Usually there are several IF channels that cover different velocity ranges, while the reference velocity channels are included only in one of the IF channels. In this case, solutions obtained in this IF channel should be copied to other IF channels. This can be made by the task `SNCOR` with setting the adverbs `OPCODE='CPSN'` and `SNCORPRM=` *[IF channel containing true solutions]*.

11.4 Self-calibration using maser data

At this stage, the reference velocity channels are split for self-calibration. To keep the file structure that has the same number of IF channels and Stokes types, when performing the task `SPLIT` only the adverbs `BCHAN` and `ECHAN` are modified (see also section 7.1.2). Even if an IF channel containing the reference velocity
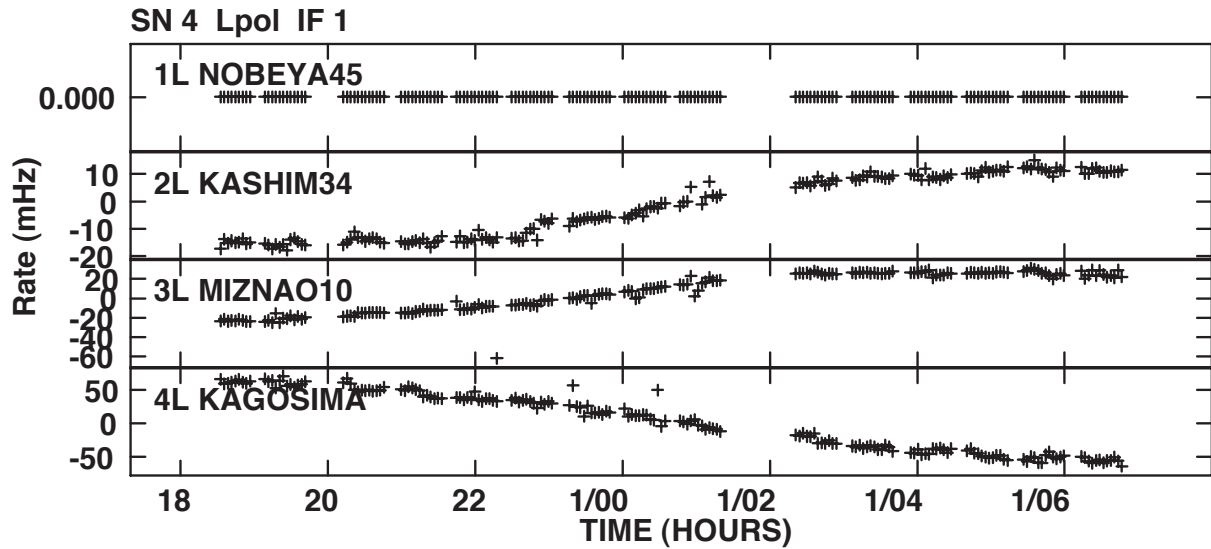
Figure 11.2: Fringe-fitting solutions (rate residuals) that are obtained with the LkHα234 H$_2$O maser emission in the selected velocity channels.

channels is used in self-calibration and hybrid mapping, *all IF channels* should be split at this stage.

The self-calibration process in the remaining parts is the same as that described in sections 7.1.3 and 7.2.1. There are two important notes as follows.

(1) In the task `IMAGR`, the adverbs `BIF` and `EIF` should be specified to select only one IF channel containing the maser emission. On the other hand, in the task `CALIB`, all IF channels should be specified. As results many solution failures occurs at IF channels without maser emission. This does not matter for maser data calibration. Instead, solutions in the IF channels containing the maser emission should be checked with the task `SNPLT`.

(2) All `SN` tables are necessary to update the existing `CL` table in step-by-step. All of the `SN` should copied to the original (multi-source) UV data, edited with the task `SNCOR` in the same procedure as that described in section 11.3, and applied with the task `CLCAL`.

(3) If the tasks `MULTI` and `INDXR` are not used in the previous step, the task `IMAGR` uses an `SN` table that is created in a previous step to use the task `CALIB`. In this case, only final `SN` table is used for calibrating the original visibility data without any update of `CL` tables.

Chapter 12

Search for maser emission

In practice, maser emission, especially H_2O maser emission is found in a huge sky area and in a wide velocity coverage. Sometimes it covers up to 10 arcseconds and quite *huge* for VLBI imaging. There are as many as 1000 spectral channels having maser emission. In these case, it is impossible for one CLEAN image cube to cover the whole maser emission region with over $(10^4 \times 10^4)$ grids. From the beginning, it is quite difficult to look for such maser emission in CLEAN image cubes. Here, how maser emission is looked for in the wide sky field is described.

Sometimes it is forgotten that VLBI images lose their *absolute coordinates* after fringe fitting and self-calibration. Here how the absolute coordinate is estimated is also described.

12.1 Field of view of maser source data

Field size of maser distribution is the most severe factor of all the data reduction procedures. It is a good idea to estimate the size of field of view for the data before choosing the methods of maser emission search.

The complex visibility $V(u, v, w)$, which is obtained after cross correlation with delay tracking and fringe rotation from a two element interferometer with a baseline vector (u, v, w) when observing the source with brightness distribution $B(\xi, \eta)$, is described as follows,

$$V(u,v,w) \ = \ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(\xi,\eta) B(\xi,\eta) \exp\left(-2\pi j \left[u\xi + v\eta + w(\sqrt{1-\xi^2-\eta^2}-1)\right]\right) \frac{d\xi d\eta}{\sqrt{1-\xi^2-\eta^2}}, \quad (12.1)$$

where (u, v, w) has a unit of wavelength of the observed radiation and is defined with respect to the celestial position in the correlation processing, (ξ, η) is position offset from the above assumed position, $A(\xi, \eta)$ is the geometric mean of the beam pattern of the telescope assuming the telescopes accurately turned to the above assumed position (see also Eq. 3.13 of text [23]). Here there are three criteria to determine the field of view. For astronomical masers, 'bandwidth smearing' can be ignored because of narrow frequency spacing of each maser component.

I. We usually obtain simultaneously the real and imaginary parts of the visibility shown in Eq. 12.1 and calculate visibility amplitudes and phases. The obtained visibilities are time-averaged for a parameter (accumulation) period (0.1–10 s) with delay tracking and fringe rotation using one set of the tracking parameters (e.g., geometrical delay). The fringe phase, therefore, is smeared and fringe amplitude is reduced because the tracking parameters should change during the parameter period with the Earth's rotation. Thus, 'the time average smearing' gives the limit on the filed of view under the criterion shown approximately as follows,

$$1 \, rad \geq \Delta\phi \simeq 2\pi \Delta\tau \omega_e D_\lambda \cdot \Delta\theta, \quad (12.2)$$

where $\Delta\phi$ is a phase shift during a parameter period, $\Delta\tau$ duration of the parameter period, ω_e angular velocity of the Earth's rotation, D_λ projected baseline length in unit of wavelength, $\Delta\theta$ the field of
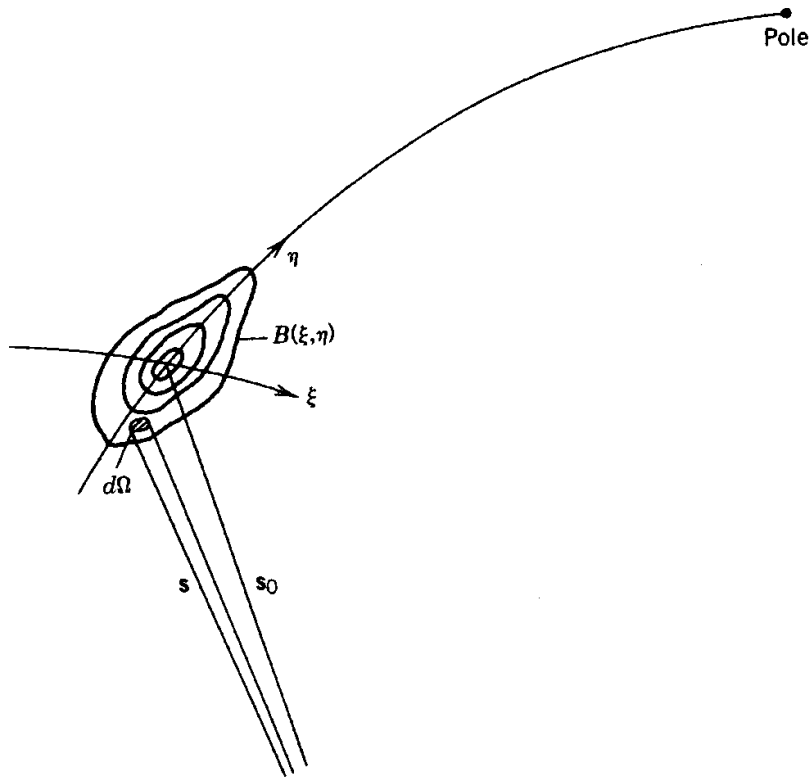
Figure 12.1: Geometrical relationship between a source under observation $B(\xi, \eta)$ and an interferometer or one antenna pair of an array. The spacing vector D_λ of the telescopes has components (u, v, w). The figure is cited from figure 3.2 of the text [23].
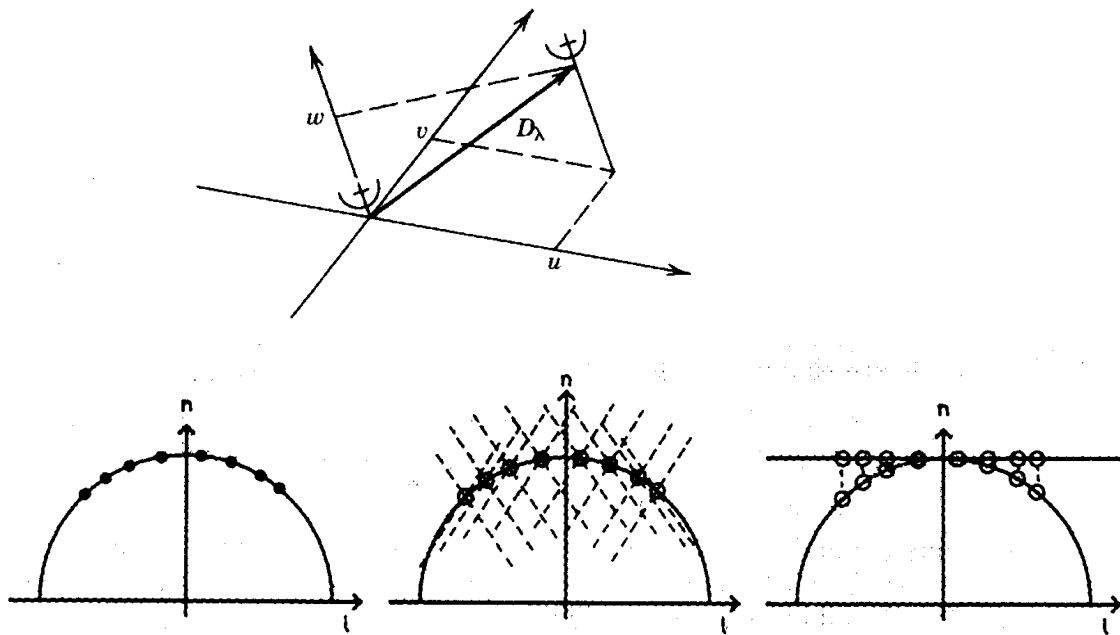
Figure 12.2: Image volume and its relation to the sky brightness along the one image coordinate $l(\xi$ or $\eta)$. n shows the direction of the map center. The direction is called as 'a phase-tracking center' when phase shifting is made to shift the map center. *(Left)* Three-dimensional transformation of the analytic visibility function maps the sky brightness onto a unit sphere. The dots represent these sources. *(Middle)* Convolution with a dirty beam results in sidelobes, shown as dashed lines. The direction of the dashed lines rotate as the Earth rotates. *(Right)* The two-dimensional image is recovered by projection onto the tangent plane indicated by vertical dashed line. The separation between two sources is more significantly different on the tangent plane from that on the unit sphere at point with larger distance from the direction n.

view. This equation means that the observation with the longer baseline corresponds to the smaller field of view. The field of view is,

$$\Delta\theta[as] \ \leq \ 14.2\frac{\lambda[cm]}{\Delta\tau[s] \ D[1000km]}. \tag{12.3}$$

For example, the field of view of about 7″ is obtained when the baseline length is 3000 km, the observed wavelength is 1.35 cm (H_2O 22 GHz water maser) and the parameter period is 1″. If the field size of maser distribution or separation between the reference and target source is larger than the field limit, we must perform the data correlation separately assuming the source positions at several celestial points or at both the reference and target sources. The output data, therefore, increases with the number of the correlation positions.

II. The field of view of the single CLEAN map is limited more severely. The image synthesis is made on the single plane, while the actual source brightness distribution is on the sphere of the sky. The effect on imaging by the position discrepancy between the two planes is shown in Fig. 12.2. The shape of the image or the brightest point of the source should be changed at edge of the wide field map.

Thus, 'the polyhedron imaging' has the limit on the filed of view under the criterion shown approximately as follows,

$$(D_{\boldsymbol{\lambda}} \cdot \boldsymbol{\sigma})^2 \leq a, \tag{12.4}$$

where, $D_{\boldsymbol{\lambda}}$ is a baseline vector of the telescope pair, $\boldsymbol{\sigma}$ is position offset from the map center, and a is a factor to determine the criterion, usually 1/20 or 1/25. In conclusion, the limit of field of view for 'the polyhedron imaging', in unit of radian, is given as follows,

$$\Delta\theta \leq \sqrt{\lambda/D}/5 \approx \sqrt{\theta_{syn}}/5, \tag{12.5}$$

where θ_{syn} is a synthesized beam of the interferometer. For example, when the synthesis beam is 1 mas, the field of view of the single plane map is limited to about 2″.8.

III. Of course, a primary beam of a telescope absolutely gives a limit on field of view.

12.2 Long-time data integration

After full calibration that has been mentioned above, coherent integration for the whole observation time gets possible. The task `POSSM` makes cross-power spectra performed such long-time integration. Figure 12.3 shows cross-power spectra with an integration duration of as long as 12 hours. H_2O maser components weaker than 1 Jy are now detected. If setting the adverb `NPLOT=0`, data in all baselines specified are averaged to make a cross-power spectrum of the VLBI array.

Note that scalar and vector averages (setting the adverb `APARM(1)=1` and `=0`, respectively) provide different cross-power spectra. The former is similar to that obtained in total-power spectra in which most of all maser emission is detected. Therefore the former is used to find faint maser emission. The latter, on the other hand, is affected by array configuration and the source structure. The latter is used, for example, to estimate rough location of faint maser emission that cannot be detected in the fringe-rate mapping mentioned in the next section.

12.3 Fringe-rate mapping

Fringe-rate mapping method has been described in detail in these documents ([27, 19, 18]). Fringe phases enable us to make synthesized images that performs inverse Fourier transform of visibilities. The fringe phases, however, are affected by many factors and themselves have 2π-n radians ambiguity problems. In early VLBI observations, fringe rates have been used as major observable parameters. Nowadays, fringe rates are still important to make *rough* maps with wide fields of as large as several tens of arcseconds. Because
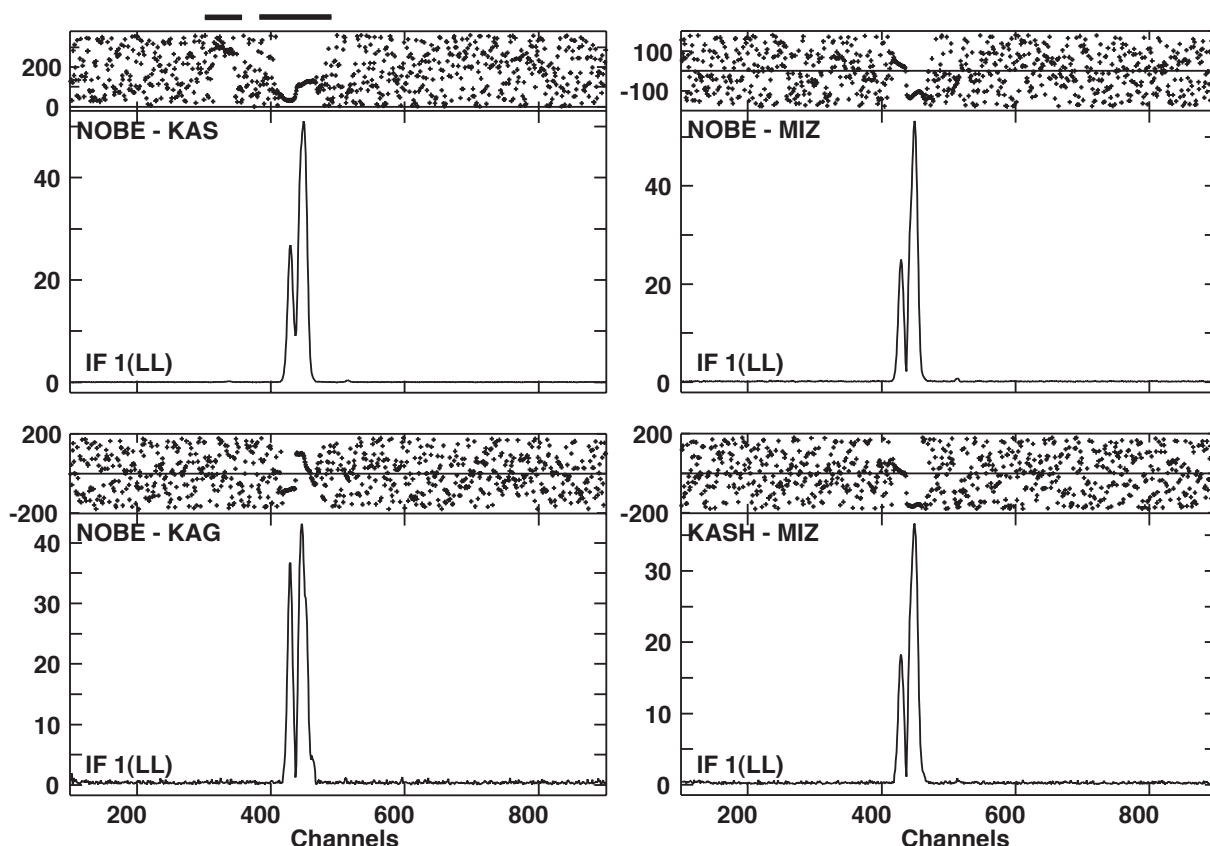
Figure 12.3: Cross power spectra of the LkHα234 H_2O masers that are obtained by integration for the whole observation time (12 hours). Bars on the top of the spectrum of Nobeyama–Kaashima baseline indicate detection velocity ranges of the H_2O maser emission, in which clear phase slopes are seen.

fringe rates do not have any ambiguity, they are also used to estimate absolute coordinates of the target sources after applying clock parameter calibration.

A fringe rate spectrum is obtained by Fourier transform of a cross-correlation function against time in a spectral channel (see [19, 18]). A relative fringe frequency, a relative fringe rate multiplied by the observed frequency ν_f is expressed as follows,

$$\Delta\nu_f \simeq \dot{u}\Delta\alpha\cos\delta + \dot{v}\Delta\delta. \tag{12.6}$$

where $(\dot{u}, \dot{v})$ are the time-variation rate of a baseline vector. Thus a fringe frequency is a linear function of source coordinates; one line is drawn on the fringe-rate map as shown in figure 12.4. Because $(\dot{u}, \dot{v})$ varies more slowly than the baseline vector (u, v), wide-field mapping is possible.

Note, however, that the fringe-rate mapping is unavailable for sources very close to the celestial equator ($|\delta| \leq 10°$) because most of the lines shown above are almost parallel to the north–south direction and it is quite difficult to identify the location of maser spots.

12.3.1   Wide field mapping with relative fringe rates

Fringe-rate mapping has been used to make mainly maps of H_2O masers having very wide fields of maser spots distribution (e.g. W3OH, Orion KL, W49N, etc.) and CH_3OH masers whose observations could use only a few telescopes that have the receiving systems covering the special frequency band (e.g. 6.7 GHz). The accuracy of such kind of position estimation is limited by the phase (rate) fluctuation due to the atmosphere and empirically achieved around 100 times as poor as the synthesized beam size of the VLBI array.

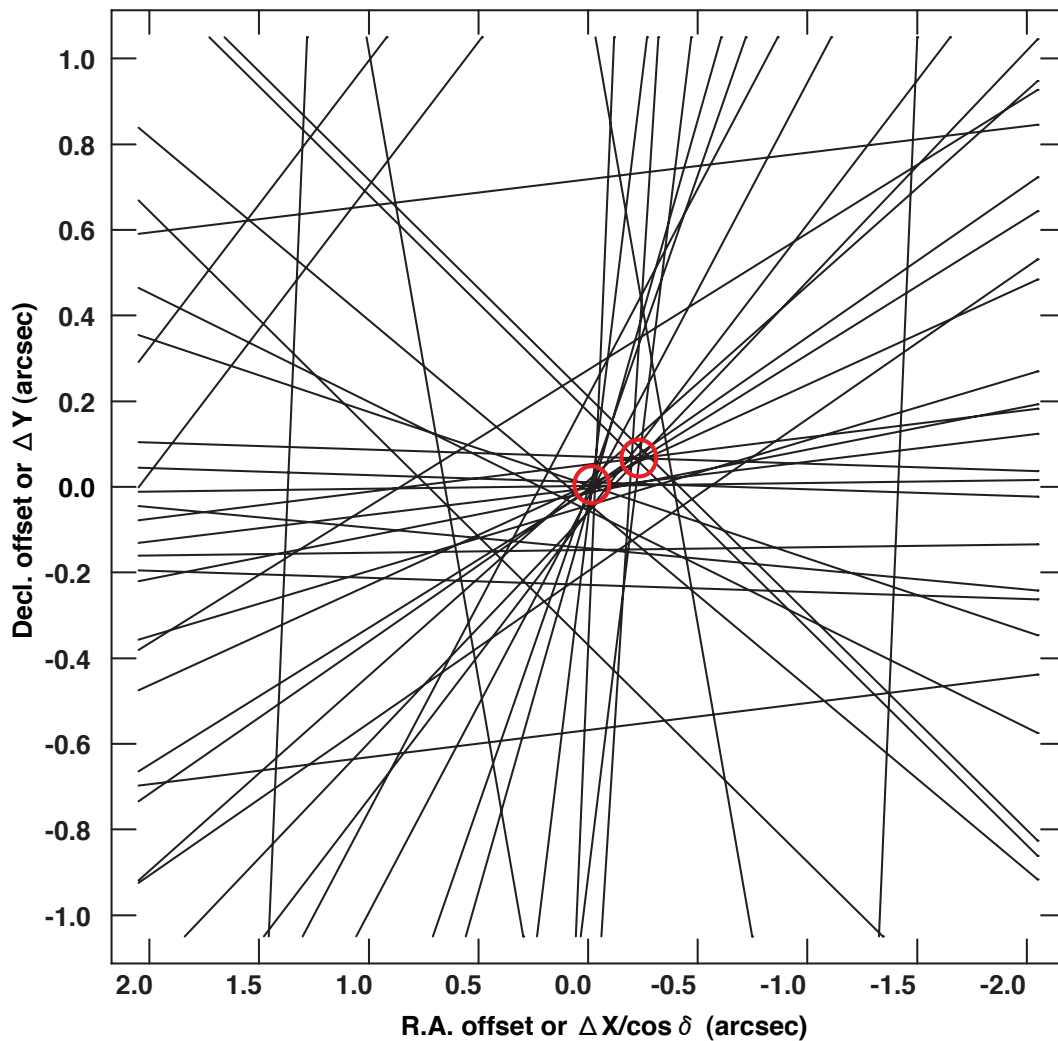The task `FRMAP` performs the fringe-rate mapping as follows.

Figure 12.4: A fringe-rate map for a group of selected velocity channels containing H_2O maser emission in LkHα234. Two red circles indicate the locations of the H_2O maser spots. Each of the lines were obtained by integrating the visibility data for 15 minutes. 10 lines were omitted in the iterative process in identification of maser spots.

```
TASK 'FRMAP'      Call the task FRMAP
INDISK 1; GETN 100    Get UV data used for the mapping.
SOURCES  'LKHA234'        Maser source name
UVRANG   0        UV range limit is useful when making wide-field maps.
TIMERANG  0              Time range to be selected, useful for precisely getting maser data.
STOKES  'I'             Stokes parameter 'I' is used for the mapping.
BIF  1                 IF number including maser emission.
BCHAN 440; ECHAN 446    Begin and end of velocity channels plotted.
CHANNEL=-1              No channel for phase reference in the mapping is specified.
ANTENNAS m1            Antennas with high sensitivity are specified.
BASELINE  0           All baselines with ANTENNAS.
DOCALIB   2            Calibrate with a CL table and weights.
GAINUSE  9             CL table version to be applied.
FLAGVER  0            Flag table version.
DOBAND   1            Apply a BP table.
```

```
BPVER    1                 BP table version to be applied.
APARM(1) 2                  Pre-average interval in second, similar to a parameter period.
APARM(3) 5                 Number of spectral channels to be averaged.
APARM(4) 50; APARM(5) 100    R.A. and decl. steps of a map grid to find maser emission (mas).
APARM(6) 2000; APARM(7) 1000   Half widths of a map on the sky in unit of mas.
BPARM(1) 10                Threshold (in sigmas) in detection maxima in fringe spectrum.
BPARM(2) 70                 Time interval between beginnings of interval of averaging (min).
BPARM(3) 15                 Interval of averaging  in unit of minute.
DOTV   1             Plot a fringe-rate map on the AIPS TV Server.
INP; GO
```

There are special notes for the adverbs in the task FRMAP to work appropriately.

- CHANNEL: The task FRMAP works appropriately even before full data calibration has not made yet. In this case, this adverb sets a phase-referencing channel, whose phases are subtracted from all spectral channels before obtaining fringe-rate spectrum.

- TIMERANGE: Because data are picked up uniformly along time by following the adverbs BPARM(2), BPARM(3), specifying this adverb enables us to get more visibility data from the selected source.

- BPARM(1): Smaller number for a wider field, larger number for quicker processing.

- BPARM(2), BPARM(3): Because less than 11 fringe-rate spectra are available in each of baselines, these adverbs should be set appropriately.

- BPAEM(6): Minimum number of lines that cross the same point, or a maser spot location, on the sky. The input value is multiplied by the number of lines per baseline and by the number of baselines. To find fainter maser emission, a smaller number (say 0.2) is suitable.

12.3.2   Estimating absolute coordinates of the maser source

Absolute coordinates of maser sources are quite important information especially to make image cubes having a velocity range over several tens of kilometers.

For example, suppose maser spots that are found in different Doppler frequency channels separated by up to $\Delta\nu$. If the absolute source coordinate has a position uncertainty Δs, an uncertainty of *relative positions* among the maser spots σs is derived from the following equations,

$$\nu \frac{D \cdot \sigma s}{c} \sim \Delta\nu \frac{D \cdot \Delta s}{c}, \quad \sigma s \sim \Delta s \frac{\Delta\nu}{\nu} \tag{12.7}$$

By inserting, for example, $\Delta s \sim 100$ mas, $\Delta\nu/\nu \sim 1/1000$ (corresponding to a Doppler velocity of 300 km s^{-1}), an error of 10 μas in the relative maser spot position is derived.

Estimation of the absolute coordinate is made after fundamental calibration (see section 6) with continuum calibrators but before fringe fitting with the target maser source. This means that the calibration (CL) table used here shall be obtained by applying a solution (SN) table as obtained in section 6.5. The accuracy of such kind of position estimation is limited by the phase (rate) fluctuation due to the atmosphere and empirically achieved around 100 times as poor as the synthesized beam size of the VLBI array.

12.4   CLEAN image cubes having multiple wide fields

To make image cubes of maser sources, the UV data that are calibrated using the data in reference velocity channels of maser emission are at first split to a single source file using the task SPLIT with applying the latest CL table and FG, BP (if not applied yet) tables that are already prepared (see section 7.1.2). An *image cube* consists three channel axes, R.A. and decl. offsets and velocity or frequency channels.

The task IMAGR has been explained in more detail in section 7.2.2. Here, the adverbs in the task, which are essential for creating maser image cubes with multiple fields, are described as follows.

```
DOCALIB=-1; DOBAND=-1    Not applied any CL or BP table, which is already applied.
BCHAN k1; ECHAN k2       Making image cubes covering channels from k1 to k2.
NCHAV  1          Every velocity channel is mapped independently.
CHINC  1          All channels without skipped channels are used.
BIF m1; EIF m1   The IF channel m1 is selected.
NFIELD   5        Multiple fields including maser emission are CLEANed at the same time.
DO3DIMAG 0        If pos. offsets are large, using different tangent points are recommended.
FLDSIZE 1024     Wider field (1024 x 1024 pixels) for looking for maser emission.
RASHIFT 0, -.07, .28, .08, -.07   R.A. shifts for the individual fields (arcsec).
DECSHIFT 0, .13, .25, .13, -.13   Decl. shifts for the individual fields (arcsec).
UVTAPER  0        If the source is extended, (Gaussian taper may be necessary (kilo-lambda).
UVRANGE  0        If necessary long (U, V) distance having poor data quality is no used.
UVWTFN 'NA'      To get a sharp beam, uniform weight (UF) is recommended.
NBOXES 0; CLBOX 0  Search CLEAN components in the whole maps.
OVERLAP 1         Restore CLEAN components in overlapped fields.
DOTV=-1           Automatic imaging without human interaction makes the process fast.
```

    After looking for true maser spots, a user can compress the mapping fields and velocity channel ranges
to save file size and time for model fitting (see section 14.2).

12.5   Quick statistics of image cubes

Here the task IMEAN is useful to quickly find maser emission (see section 7.2.3). When setting the adverbs
DOCRT=1 and OUTPRINT=*[output text file name]*, all results in the task are printed out to the specified file.
By using the keyword "Maximum", a user quickly find the peak intensity in the image cube. Because an
image cube is usually made the statistical analysis channel by channel, a simple RUN script shown as follow
is easy to quickly make such procedures.

```
proc pkfnd
  dowait=1
  scalar xg,yg,xmg,ymg,ix,iy,nx,ny,nedge,nover,px,py,bvel,evel,iv
  nx=xg/xmg; ny=yg/ymg

  task 'imean'
  docat=-1;dotv=-1;docrt=-1
  for iv=bvel to evel
  for ix=1 to nx
    for iy=1 to ny
      px=xmg*(ix-1)+1-nover
      if(px < nedge) then px=nedge; end
      py=ymg*(iy-1)+1-nover
      if(py < nedge) then py=nedge; end
      blc px, py, iv
      px=xmg*ix+nover
      if(px > xg-nedge) then px=xg-nedge; end
      py=ymg*iy+nover
      if(py > yg-nedge) then py=yg-nedge; end
      trc px, py, iv
      go imean
    end
  end
return;finish
```

In the above script, a user specifies newly defined adverbs, XY, YG, XMG, YMG, NEDGE, NOVER, BVEL, EVEL. To
find more than one maser spots in a velocity channel, sub-fields are specified, in which only one maser spot
with the maximum intensity is picked up.

Chapter 13

Creating final image cubes

After full calibration procedures, one can finally get image cubes and use them for scientific purposes. For high-precision astrometry, more careful corrections for the image cubes should be performed. Of course, backups for the data and image cubes finally obtained shall be performed. Figure 13.1 presents a flow of such final procedures.

13.1   Final CLEANed image cubes

After searching for true maser spots in wide fields, as shown in section 12.3 or 12.4, only fields and velocity channels close to the true maser spots found are created.

13.2   Making full maser image in a single map

Maser source data usually has a form of a *image cube* (X-offset, Y-offset, V-offset). To show all of maser spots found in different velocity channels into a two-dimensional map (example, see figure 13.2), the following sequence is useful.

(1)   Use the verb `IMSTAT` to find a rms noise level for each of velocity channels.

(2)   Use the task `BLANK` to set intensities of pixels without true maser emission to zero. At this stage, image files for the individual velocity channels are obtained.

(3)   Use the task `SUMIM` to sum image files for the individual velocity channels into one map.

The task `SQASH` is also used to compress the file of the `BLANK` output into one map, but the obtained map may by noise. It is because noise is not appropriately omitted in the task `BLANK` in velocity channels in which bright maser emission creates bright side lobes. It is difficult to omit only the side lobes without deleting fainter true emission in other velocity channels.
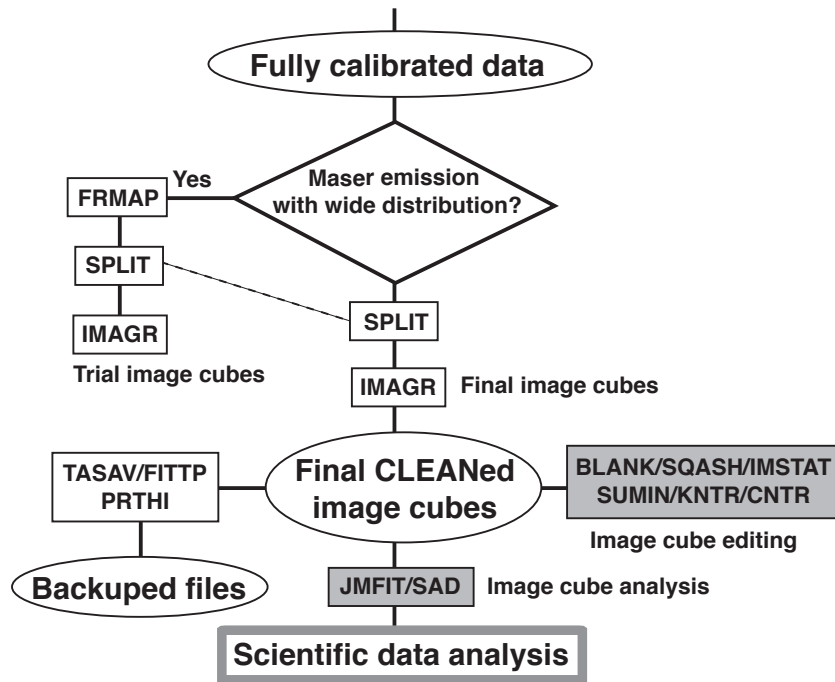
Figure 13.1: Flow chart of the part that describes creating image cubes and final processing in AIPS and VLBI analysis.
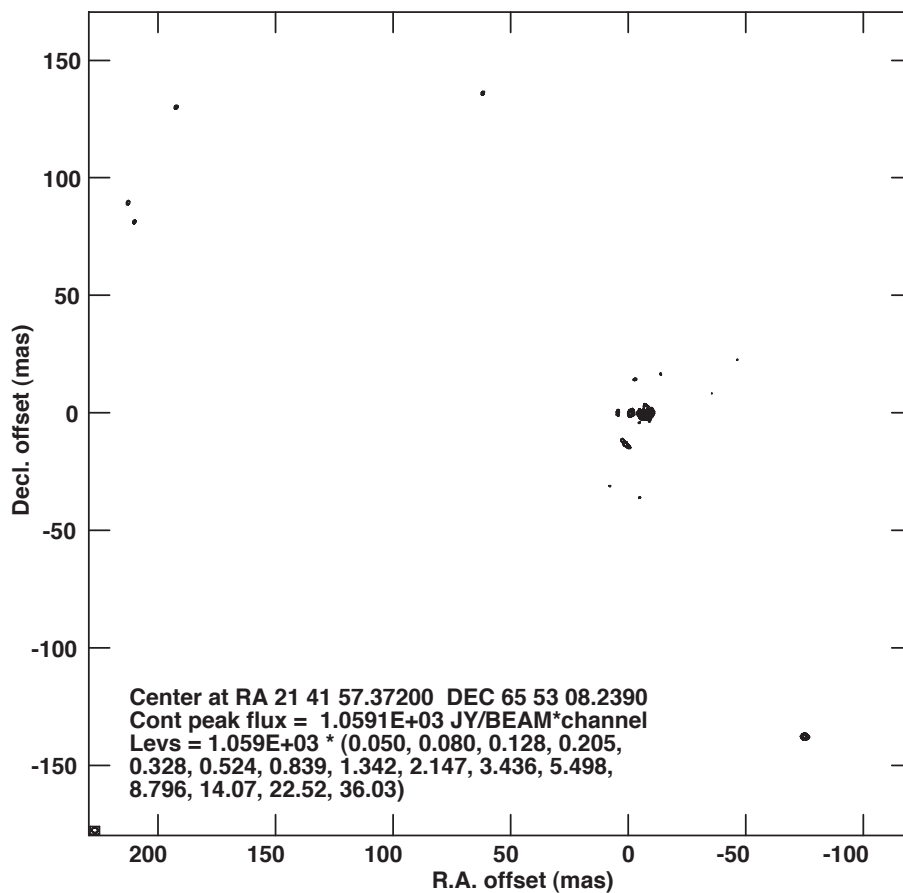

Figure 13.2: Full map of the LkHα234 H$_2$O masers, which was made by a sequence of the tasks and verbs IMSTAT, BLANK, SUMIM and KNTR. The brightest maser feature at the map origin has a peak intensity of 78 Jy/beam and sidelobes. There are weak maser features have peak intensities less than 4 Jy/beam, which can still be seen in the map because different blank cutoffs (but unified at a 6-σ noise level) in the task BLANK were set in the individual velocity channels.

Chapter 14

Getting physical parameters

14.1 Identification of maser spots and features

Definitions of a *maser spot* and a *maser feature* are described in the papers [10, 15]. The maser spot is a single velocity component of the maser emission. A maser feature is a group of the maser spots with similar positions and velocities (within a few mas) and a few kilometers per second, respectively). These definitions are important to identify true maser emission. True maser spots should be detected at almost the same location among successive velocity channels. A group of such maser spots is defined as a maser feature z and calculated its location and velocity in the next process.

14.2 Gaussian fitting to maser spots

Gaussian bright distribution models for maser spots are calculated with the task `JMFIT`. According to author's experience a large fraction of time has been consumed in this part. Because the task `JMFIT` requests suitable fitting boxes (the adverbs `BLC` and `TRC` and assumptions of the number of Gaussian components (the adverb `NGAUSS`, as well as the adverb `GPOS` specifying their locations).

At present the task `SAD` (Search And Destroy) automatically performs the identification of Gaussian components and their fitting.

Chapter 15

Data backup

Here how to make data backup is described. The calibrated visibility data can be fully saved on DAT tapes or FITS files. However, because the visibility data themselves are quite huge, there is an idea to save only the necessary parts used for quickly recovering the calibrated visibilities and image cubes. It is also a good idea to save the created image cubes for quickly using specific scientific purposes or for shipping them to other collaborators or scientists.

15.1   Back up AIPS UV data and images

All of the AIPS UV data and image files are saved on DAT tapes or FITS files on hard disk drives with the task `FITTP`. It takes long time, however, to save on DAT tapes for the present huge data.

15.2   Backup only extension tables

The task `TASAV` splits only extension tables from the original visibility data. Only the extension tables are needed to make the backup copies, which can be quickly applied to the original visibility data by copying with the task `TACOP`.

Chapter 16

Scientific analysis

Although distributions of maser features only on the sky plane and the line-of-sight velocity are impressive, proper motions of the maser features provide great advantage in scientifically interpreting the observational results with small amount of assumptions and often without ambiguity in the interpretation. Therefore, this text concentrates on actual steps for the proper motion measurements.

16.1 Proper motion measurement

16.1.1 Astrometric correction

The obtained maps of a maser source is usually deformed by several factors that shall vary with observing epochs. Therefore maser maps obtained at the different epochs are deformed in different amount. *The astrometric correction* recovers such bending effects as follows. The correction includes scale correction and axis rotation.

The scale correction should be performed along the line-of-sight velocity because the phase-reference technique using reference velocity channels gives the similar phase drift due to the clock delay offset if the maser spot in the reference channel has a position offset with respect to the tracking center in the data correlation. This correction $\Delta\boldsymbol{\theta}(v)$ is performed for the maser spot with the LOS velocity v using the following equation,

$$\Delta\boldsymbol{\theta} \; = \; \frac{v - v_{ref}}{c}\boldsymbol{\theta}_{ref}, \tag{16.1}$$

where v_{ref} is the line-of-sight velocity of the phase-referenced maser spot and c is a speed of light, $\boldsymbol{\theta}_{ref}$ is a position offset of the phase-referenced maser spot with respect to the phase tracking center in the data correlation.

Axis rotation occurs when conversion of the coordinate epoch is performed from the standard epoch (e.g. J2000) to the observing epoch in the data correlation. The coordinate conversion introduces negligible axis rotation only in the tiny field very close to the phase(delay) tracking center ($\leq 1''$). The rotation of the coordinate system strongly depends on the source position with respect to the North or South Pole.

The first step of the astrometric correction is the coordinate conversion of the phase-referenced maser feature from the original coordinate system (J2000.0) to the one at the observing session. It is easier to convert the source coordinate into the Cartesian coordinates and then rotate the coordinate system. The conversion from the spherical coordinate (α, δ) to the Cartesian coordinate $\boldsymbol{x}=(x, y, z)$ is described as follows,

$$x \; = \; \cos\delta\cos\alpha \tag{16.2}$$

$$y \; = \; \cos\delta\sin\alpha \tag{16.3}$$

$$z \; = \; \sin\delta. \tag{16.4}$$

Here, the coordinate rotation matrixes around x-, y- and z-axis are denoted as $\boldsymbol{R}_x(\theta)$, $\boldsymbol{R}_y(\theta)$ and $\boldsymbol{R}_y(\theta)$, respectively, where θ is the rotation angle in the counter-clockwise direction. Then the coordinate rotation from $\boldsymbol{x}$ to $\boldsymbol{x}'$ by precession and nutation is described as follows,

$$
\begin{aligned}
\boldsymbol{x}' &= \boldsymbol{N}(\Delta\psi, \Delta\epsilon)\boldsymbol{P}(z_A, \theta_A, \zeta_A)\boldsymbol{x} & (16.5) \\
\boldsymbol{N}(\Delta\psi, \Delta\epsilon) &= \boldsymbol{R}_x(-\epsilon - \Delta\epsilon)\boldsymbol{R}_z(-\Delta\psi)\boldsymbol{R}_x(\epsilon) & (16.6) \\
\boldsymbol{P}(z_A, \theta_A, \zeta_A) &= \boldsymbol{R}_z(-z_A)\boldsymbol{R}_y(\theta_A)\boldsymbol{R}_z(-\zeta_A), & (16.7)
\end{aligned}
$$

where z_A, θ_A, ζ_A are the precession angles, $\Delta\psi, \Delta\epsilon$ are the nutation angles.

The coordinate conversion for annual aberration from $\boldsymbol{x}'(x', y', z')$ to $\boldsymbol{x}"(x", y", z")$ is approximately performed as follows,

$$
\begin{aligned}
x" &= \{x' + \pi\gamma\cos l + \kappa\sin l\}/\rho" & (16.8) \\
y" &= \{y' + (\pi\gamma\sin l - \kappa\cos l)\cos\epsilon\}/\rho" & (16.9) \\
z" &= \{z' + (\pi\gamma\sin l - \kappa\cos l)\sin\epsilon\}/\rho" & (16.10) \\
\rho" &= \sqrt{x"^2 + y"^2 + z"^2}, & (16.11)
\end{aligned}
$$

where $\gamma, \kappa, \epsilon, l$ are the parameters of the Solar position with respect to the Earth. If the source is looked at near the Sun (within a few ten degrees), we should consider the relativistic defraction. In this dissertation, this factor is ignored because the maser source W3 IRS5 is on the northern sky.

In the second step, the coordinates of the maser features around the phase-referenced maser spots in the spherical coordinate system at the observing session should be determined. The relation between the relative positions in the Cartesian (x_m, y_m) and the spherical coordinates $(\alpha_m = \alpha_0 + \Delta\alpha_m, \delta_m)$ is described as follows,

$$
\begin{aligned}
x_m &= \cos\delta_m \sin\Delta\alpha_m & (16.12) \\
y_m &= \cos\delta_0 \sin\delta_m - \sin\delta_0 \cos\delta_m \cos\Delta\alpha_m, & (16.13)
\end{aligned}
$$

where (α_0, δ_0) is the coordinate of the phase-referenced maser spot. In this dissertation, this conversion was performed by using the inverted form of Eq. 16.12 changed with some approximations.

In the third, the newly specified maser coordinates should be inverted again to the coordinates at J2000.0 and converted to the Cartesian coordinates.

In the recent version of AIPS, the task UVFIX exactly performs the axis rotation described above but for the visibility data. The task recalculates the visibilities as if the data were correlated at the specified antenna coordinates and the source positions. This task shall be applied *before the fundamental calibration* (see section 6) or calibration with maser data (see section 11). Otherwise, the maser spots in the phase-reference velocity channel may have a position offset from the map origin.

Definition of position and velocity of maser feature

It is very important problem to define the positions and line-of-sight velocities of the maser features consisting of many adjacent maser spots. Usually measurements of maser positions and velocities as well as their time variation are made on the basis of positions and velocities of the maser features because the maser feature, which is actually a physical feature (cloud), is a fundamental unit of the gas kinematics. The defining methods are different from one investigator to another. Someone defined the maser feature position and velocity from the three-dimensional (x-y position and velocity) flux-averaged position for the included maser spots. On the other hand, the author have defined the maser feature position and velocity from the intensity peak in position and velocity.

16.1.2 Analysis of maser proper motions

It is quit difficult to trace motions of individual *maser spots* from one epoch to another because it is still unclear whether a motion of each of the maser spots having the same velocity traces a true motion of the physical object. At present, proper motions of *maser features* may be well measured. If one can obtain maser feature distributions observed at multiple epochs, they are superposed somehow without any precise
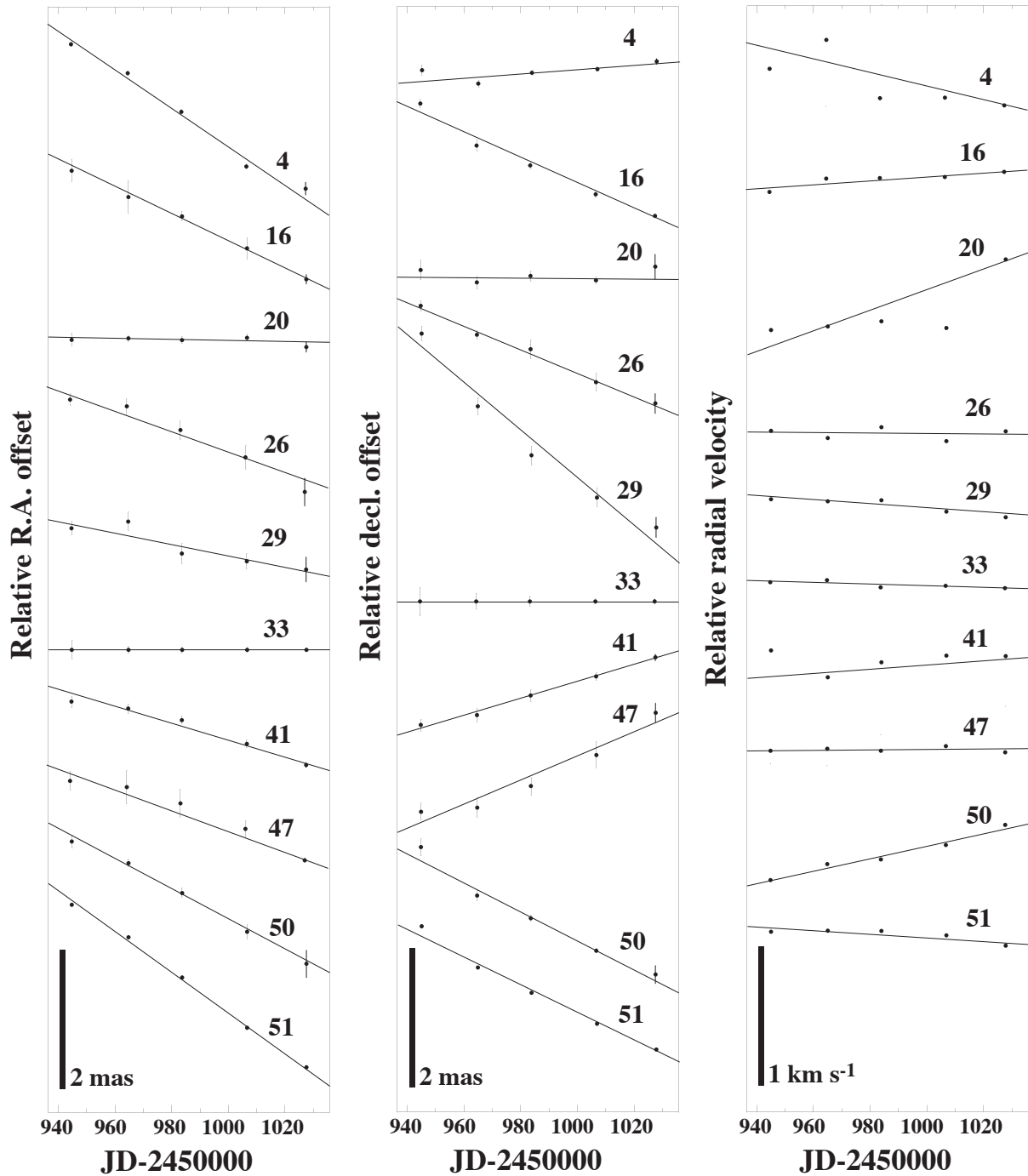
Figure 16.1: Sample of measured proper motions and the Doppler velocity drifts of maser features that had been detected in five epochs (Imai et al. 2003b). Solid lines in plots of proper motions show fit lines assuming constant velocity motions. The solid lines in the plots of the Doppler velocity drift show fit lines assuming constant acceleration motions.

common coordinate systems. Then position drifts of the individual masers with time are elucidated. They are so called *relative proper motions* of maser features.

There are two methods to superpose the multiple maps. The first, a *reference maser feature* may be selected, which has been detected at every epoch and does not change its internal structure. Figure 16.1 shows examples of relative proper motions measured for the RT Vir H_2O masers [13] in this method. This method well works for the relative proper motions, but sometimes collapses. If there are many maser futures located in a tiny sky field and velocity range, it is difficult to trace one feature between the observing epochs. Figure 16.1 also shows a few misidentifications of maser proper motions. Therefore, objective analysis is sometimes necessary. For example, one prepare many types of shifts of the maser maps and evaluate in which type maser features are best coincided each other between the observing epochs. Even if a reference maser feature is unambiguously selected, an accuracy of the proper motion measurements is limited by temporal change of the internal structure of the reference feature.

To improve an accuracy of proper motion measurement, multiple reference maser features are used to calculate mean positions of the them. The mean positions are used for superposing the maser maps. Note that both of the methods mentioned above are lost true motions of the reference feature an the mean positions, respectively. *Phase-referencing VLBI observations* that provide extragalactic reference radio sources may recover such lost information (see section 17.1.

16.2 What do maser sources trace?

Because maser emission occurs in the special physical condition and geometry in a molecular clump, maser emission traces tiny volumes in interstellar gas clouds associated with outflows from young stellar objects and mass-loss flows from Mira-type pulsating stars (see, e.g., Elitzur 1992 [9]). It has been improved, however, the apparent motions of maser clumps, or maser features, trace true kinematics of the gas clouds mentioned above. Even if a limited number of maser features detected, their proper motions provide us great information on the 3-D gas kinematics by adding line-of-sight velocities of the masers, which is not able to be revealed in thermal-line emission having widespread distribution.

16.2.1 Internal and secular motions of maser features

Figure 16.3 gives examples of maser proper motions. Because observations of H_2O and SiO masers provide us angular resolution finer than 1 mas, Many these maser sources (but less than 30 sources) have been measured their proper motions so far.

Usually, without extragalactic reference sources, maser proper motions are *relatively* measured with respect to one or a group of maser feature positions. Proper motions of the W3 IRS5 H_2O masers are in this case. (see the left side of figure 16.3. Such relative astrometry has been done so far because *absolute coordinates* of the H_2O masers are lost in the self-calibration procedure (see chapter 7) or obtained with a very poor accuracy (see section 12.3). Note that, even if the position accuracy is poorer, measurements of absolute coordinates of maser sources are important for scientific analysis. In the case of the W3 IRS5 H_2O masers, driving sources of outflows found in this regions were identified to be two of radio continuum sources observed in other observations, which also measured absolute coordinates of the continuum sources ([3]).

With extragalactic reference sources, maser positions are measured with respect to those of the reference sources. When the reference sources have accurate absolute coordinates, the absolute coordinates of the masers are also accurately measured at the same time. In such measurements, apparent motions of the masers consist of (1) internal motions of the maser source, (2) secular motions of the maser source due to, e.g., the Galactic rotation, (3) an annual parallax of the maser source. The right side of figure **??** shows the motions of the IRAS 19134+2131 H_2O masers, which trace the Galactic rotation and (marginally) the internal motions.

16.2.2 Acceleration motions of maser features

So far, proper motions of maser features have been fit to straight lines, which assume constant velocity motions. Taking into account, for example, the dynamics of stellar pulsation and orbital motions, *accelerations* may be detected especially in the kinematics of H_2O and SiO masers.
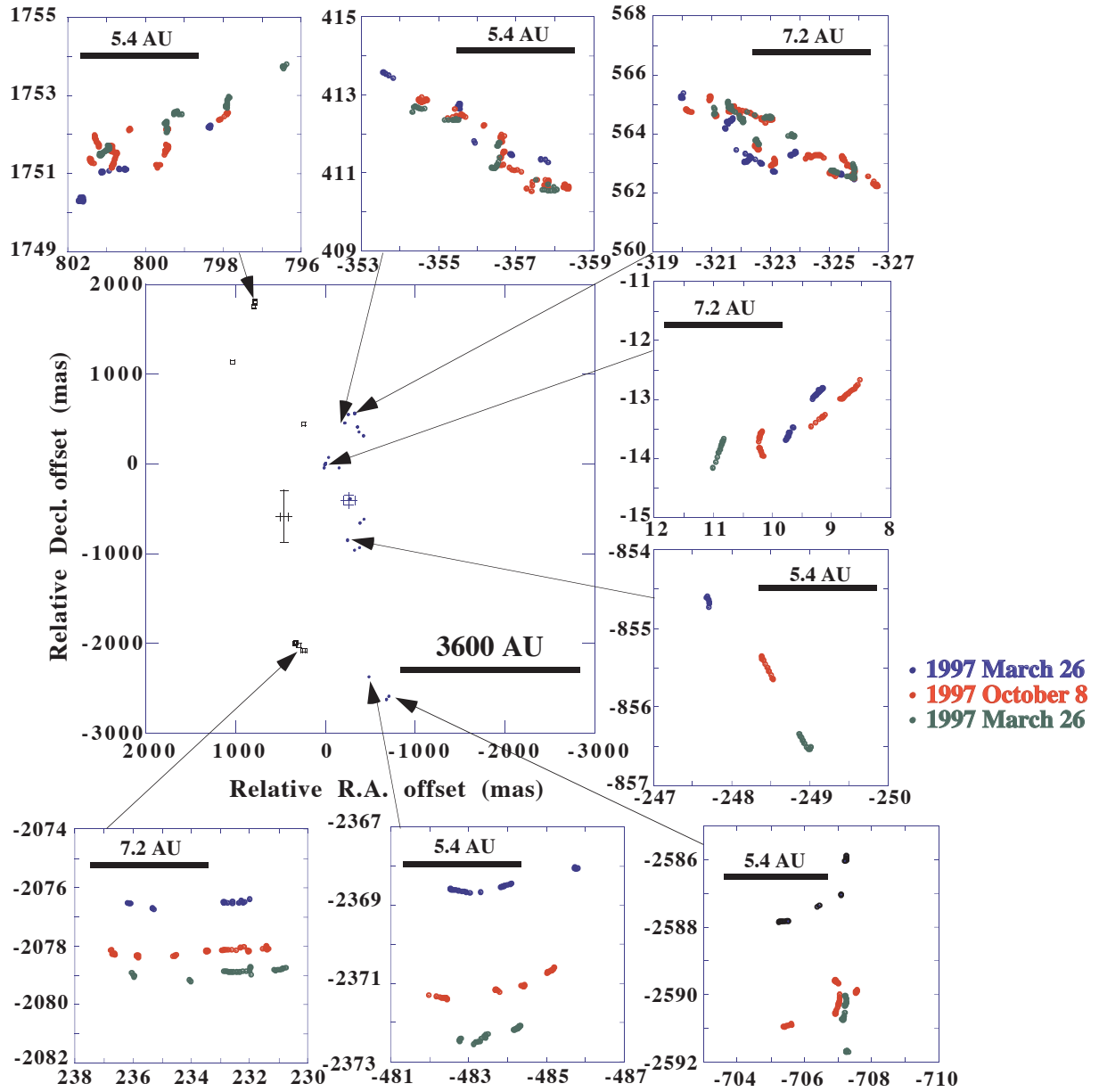
Figure 16.2: Sub-arcmillimeter structures of individual H_2O maser features and their time variation that found in the W3 IRS5 region (Imai et al. 2002b). Each of maser features, masing gas clumps, consists of *maser spots*, which have successive line-of-sight velocities and positions extended within a few of astronomical units. The pattern of spot distributions are stable within a specific period (shorter than a few months), and successively vary with time. Time gaps longer than this period in monitoring observations make us difficult to identify the same maser feature from one observing epoch to another.
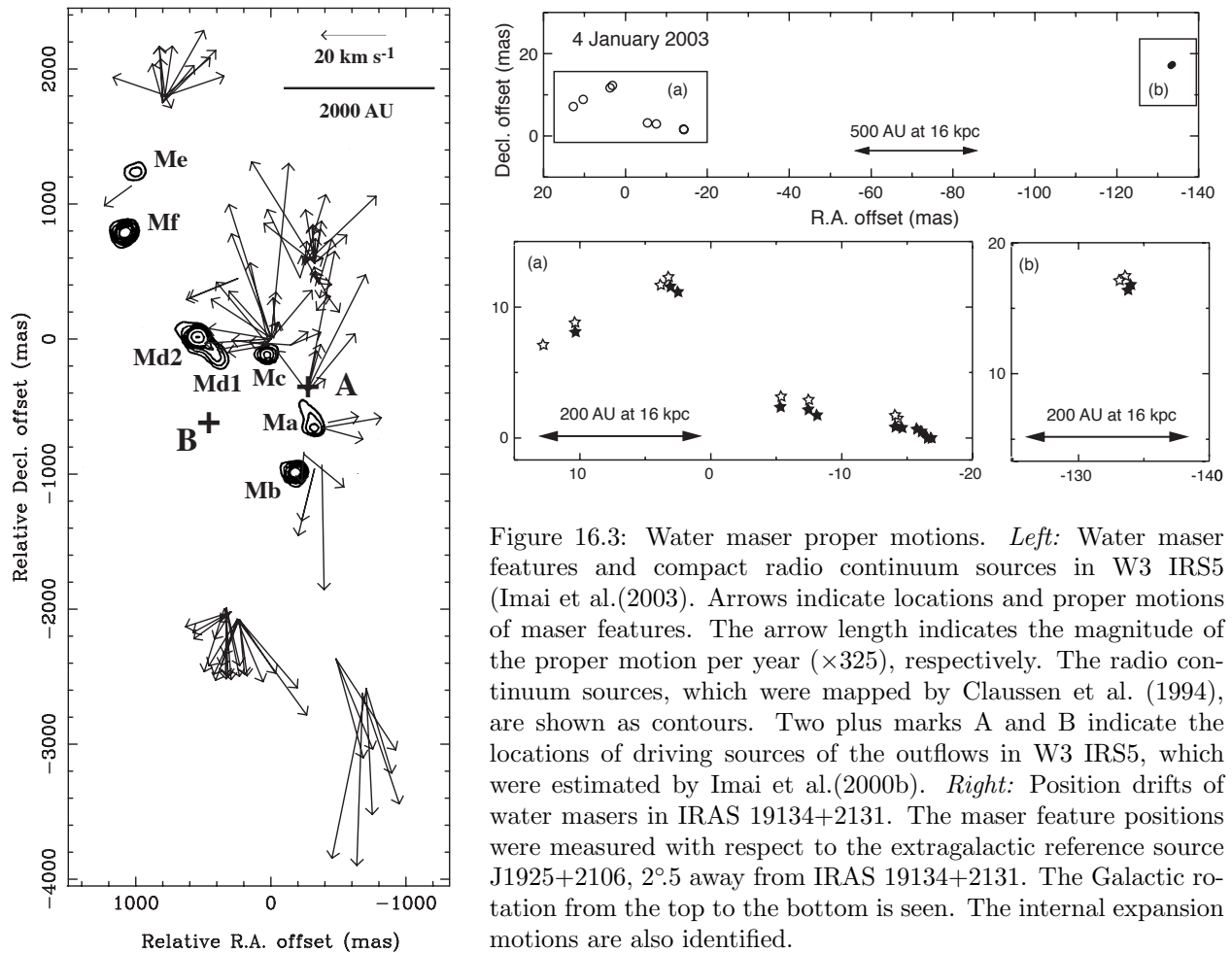
Figure 16.3: Water maser proper motions. *Left:* Water maser features and compact radio continuum sources in W3 IRS5 (Imai et al.(2003). Arrows indicate locations and proper motions of maser features. The arrow length indicates the magnitude of the proper motion per year ($\times 325$), respectively. The radio continuum sources, which were mapped by Claussen et al. (1994), are shown as contours. Two plus marks A and B indicate the locations of driving sources of the outflows in W3 IRS5, which were estimated by Imai et al.(2000b). *Right:* Position drifts of water masers in IRAS 19134+2131. The maser feature positions were measured with respect to the extragalactic reference source J1925+2106, 2°.5 away from IRAS 19134+2131. The Galactic rotation from the top to the bottom is seen. The internal expansion motions are also identified.

Figure 16.4 shows an example of detected acceleration motions in H_2O masers in the semiregular variable RT Virginis ([13]). The maser kinematics generally expresses a spherical expansion from the central star. This also traces transportation of shocks driven by stellar pulsation. In fact, one of the maser features exhibits acceleration on the sky. This acceleration motion is evident even if the maser proper motion is measured with respect to that of a reference maser feature. Such acceleration motions were discovered in SiO masers as well (e.g., [6]). If relative position accuracy of maser features achieve 10 μas, such acceleration stuff is expected to be in the scope of scientific analysis.

Even in a maser system, it has been difficult to compare the locations among different species of maser emission (OH, H_2O, SiO). For example, a Mira variable star has SiO, H_2O and OH (1612 MHz) masers in its circumstellar envelop, which are located at short to far distances from the star. It is interesting but difficult to trace a gas clump in the envelope moving from the SiO region by way of the H_2O region towards the OH maser region within a decade. Superposition of maser maps with an accuracy comparable to such gas clumps (smaller than a few astronomical units) is crucial.

16.2.3 Importance of multiple maser lines on the common reference frame

Physical conditions and locations of astronomical masers still have unclear parts. It is because their tiny volumes and different behaviors from those found in thermal-line observations make us difficult to compare the issues mentioned above with those of thermal lines that are relatively well understand. One of the difficulties comes from uncertainty in absolute coordinates of the thermal and maser lines, which are necessary to compare the expected physical conditions and to discuss the physical links between these lines.

There is another example to explain the importance of the map superposition. Figure 16.5 shows morphologies and kinematics of the W43A H_2O and OH (1612 MHz) masers in the OH/IR star W43A ([14]). In particular, the H_2O maser kinematics is well understood, which is well fit by a *precessing* bipolar jet
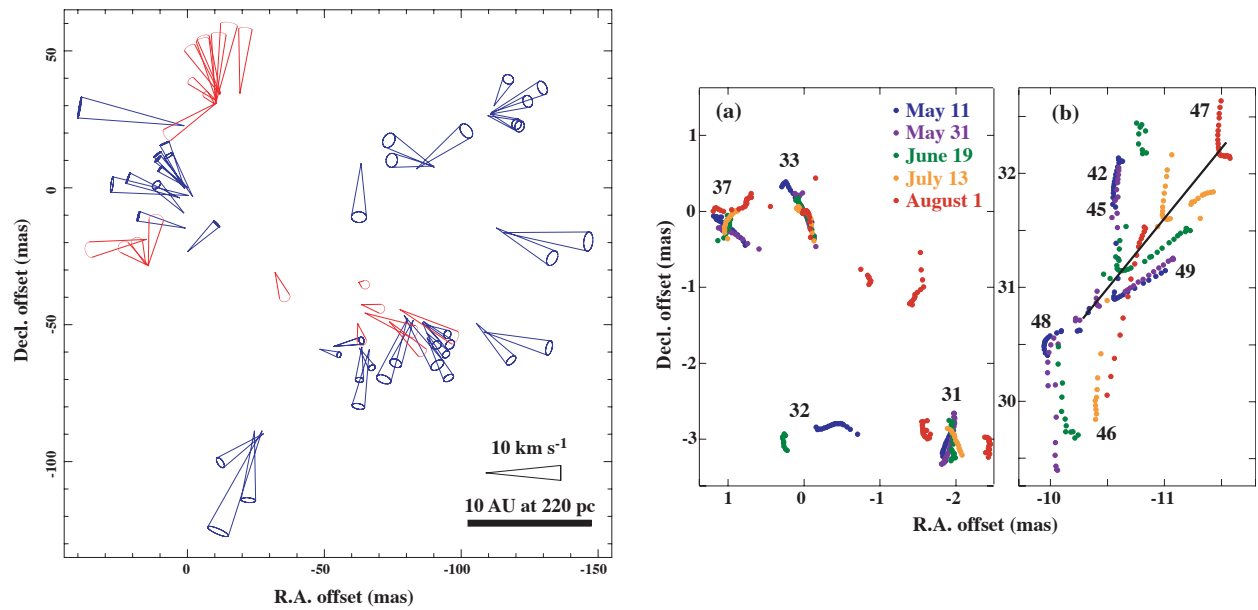
Figure 16.4: Water maser proper motions in the semiregular variable RT Virginis (Imai et al. 2003). *Left:* The 3-D velocity field of water maser features. A 3-D velocity vector of a feature is indicated by a cone. The mean velocity vector of the maser features was subtracted from each of the observed velocity vectors. The plus symbols indicate the locations of the star, estimated by the model fitting using proper motions exhibiting both expansion and infall (pink) and only expansion (green). *Right:* Spatial structures of maser features and their time variation in the two selected fields. Each of the filled circles shows a velocity component (maser spot). Radial velocities of spots change by 0.056 km s^{-1} from one spot to the adjacent spot. (a): Maser features around the map origin. A position-reference feature is spatially fixed at the map origin to make measurements of maser proper motions, but will move from south to north so that it expands with respect to the star. (b): Maser features exhibiting acceleration motions. The maser feature on a black line shows a clear constant acceleration motion and the development of its V-shaped structure. The maser feature had kept its brightness peak close to the crease of the V-shaped structure.

(see figure 16.6) and a location of the dynamical center is well estimated in the H$_2$O maser maps. It is still unclear, however, whether the dynamical center of the H$_2$O masers coincides with that of an expansion traced by the OH masers because absolute coordinates of these masers are still unclear (now in investigation). Phase-referencing VLBI observations using a common position reference source may achieve an accuracy of absolute positions better than a few mas (see section 17.1. This accuracy may solve this issues and make us understand the true character of W43A (a single star or a binary system).
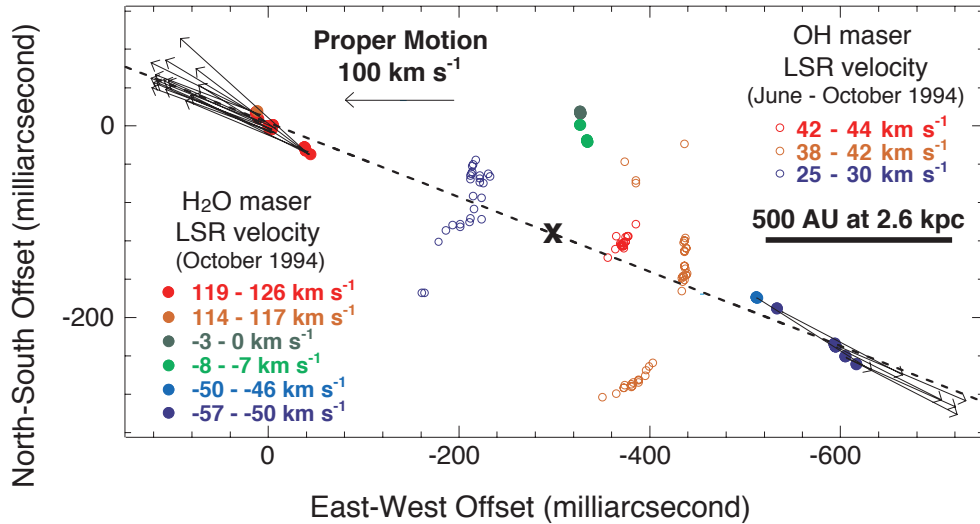
Figure 16.5: H_2O and 1612-MHz OH masers in W43A (Imai et al. 2002a) observed in 1994. Although the relative positions between the H_2O and OH masers are still under investigation in more detail, it was confirmed that they are almost the same as those shown in this figure. Dotted lines show spatial alignments of maser features in the red-shifted and blue-shifted H_2O maser clusters. A broken line shows the direction of the jet. Arrows indicate proper motions of the H_2O masers. The OH masers are well modeled by a spherically-expanding flow with an expanding velocity of ~9 km s^{-1} and a radius of ~500 AU.
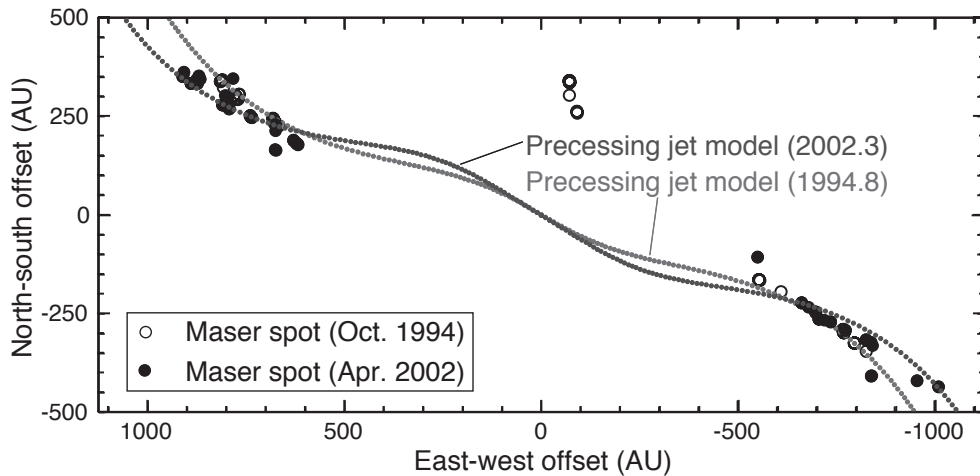

Figure 16.6: The W43A H_2O masers observed in 1994 and 2002 with the VLBA and a precessing jet model shown in dotted lines. The length of the jet has increased by ~700 AU since the year 1994. The modeled patterns were obtained from the following parameter values; a constant jet velocity of ±150 km s^{-1}, an inclination of 39° with respect to the sky plane, a position angle of 65°, a precession opening angle of 5°, and a precession period of 55 years. These values are improved from those obtained previously. It is assumed that only the direction of the bipolar ejection of material is varying continuously with time.

Chapter 17

Summary and future remarks

17.1 Phase-referencing technique

The author believes that the phrase *phase-referencing* in VLBI has been originally used for every observation and data reduction technique, in which all visibilities are calibrated using fringe phases in some part of the same VLBI data or another VLBI data. Recently, the phrase *phase-referencing technique* is used mainly for an observation and data reduction technique that uses extragalactic continuum sources as position and fringe-phase reference. The detail of the phase-referencing technique is described in the texts ([8, 1]).

Recently, a major fraction of VLBI observations adopt the phase-referencing technique to detect radio sources, which can be detected not within a coherence time (≤ 5 min) but for the whole observation time (~ 10 hrs). In this case, the reference source should be bright enough to be detected within the coherence time. There is an opposite case in which a position-reference source is detected by brighter target sources. In this case, the target source positions are determined with respect to the position-reference source. The authors has revealed that the phase-reference technique is valid for a source pairs separated by up to 3°at the 22 GHz band (e.g. [11]).

The phase-referencing technique is supported in AIPS, especially the tasks `CLCAL`, which interpolate visibility phases of target sources by solving 2π-n radians ambiguity with fringe rates. The task `UVFIX` precisely recalculates visibilities as if data correlation is made with source coordinates and station coordinates newly specified. The task `TECOR` applies calibration for total electron contents (TEC). The task `CLCOR` permits insertion of artificial excess path delays or phase offsets to recover the excess path delays due to the atmosphere, which cannot be modeled in the data correlation. Usages of these tasks may be described in author's future text.

17.2 AIPS automatic pipeline

Reduction of VLBI data, especially for spectral line sources, is a hard work. Comparing with data reduction of other observational instruments, this is a big disadvantage in astronomy and few people have tackled to such a "masochistic work" in the world [8]. This situation has recently changed by automatically running AIPS using "pipelines". A pipeline is a sequence of AIPS tasks and modules to control a pass of the tasks. The grammar of a pipeline script is quite simple such as program languages of FORTRAN, BASIC and so on. For example, data reduction of the TX Cam SiO masers (up to 75 observing epochs) [6] has been automatically made using Diamond's pipeline script. Based on this script, EVN automatic pipeline has also been developed [20]. The EVN pipeline has been released not only for personal data reduction but also for providing several services for EVN users.

Very likely, pipelines for VERA/J-Net are indispensable, which have to release observational results *every few days* because observations will be done in almost the same rate and their scientific goals should be achieved within one decade. These should be supposed taking into account that at least a few years have been consumed to publishing a scientific paper since a few of VLBI observations were made.

The AIPS pipeline has several functions useful not only to VLBI users but also to VLBI network operators and organizers as follows.

- Creating fundamental extension tables (SN, CL, FG, BP, TY, GC) for users.

- Making fundamental plots for data checking.

- Checking data quality and reliability of the VLBI network.

- Quick looking preliminary images of targets and calibrators.

- Introducing VLBI images to VLBI beginners (e.g. bachelor students).

- Automatic data reduction (in advanced use).

Programming of the AIPS pipeline scripts should be one of the most important topics in the AIPS tutorial, which will be described in the author's text. Some of the figures are obtained by segment of such pipelines.

Bibliography

[1] Beasley, A. J., Conway, J. E. 1995, in *Very Long Baseline Interferometry and the VLBA*, ed. J. A. Zens, P. J. Diamond, P. J. Napier (ASP: San Francisco), chap. 17

[2] Bridle, A. H., Schwab, F. R. 1999, in *Synthesized Imaging in Radio Astronomy II*, ed. G. B. Taylor, C. L. Carilli, R. A. Perley (ASP: San Francisco), chap. 18

[3] Claussen, M. J., Gaume, R. A., Johnston, K. J., Wilson, T. L. 1994, ApJL, 424, L41

[4] Cotton, W. D. 1999, in *Synthesized Imaging in Radio Astronomy II*, ed. G. B. Taylor, C. L. Carilli, R. A. Perley (ASP: San Francisco), chap. 17

[5] Cotton, W. D. 1995, in *Very Long Baseline Interferometry and the VLBA*, ed. J. A. Zens, P. J. Diamond, P. J. Napier (ASP: San Francisco), chap. 10

[6] Diamond, P. J., Kemball, A. J. 2003, ApJ 599, 1372

[7] Diamond, P. J., 1995, in *Very Long Baseline Interferometry and the VLBA*, ed. J. A. Zens, P. J. Diamond, P. J. Napier (ASP: San Francisco), chap. 12

[8] Diamond, P. J. 1989, in *Very Long Baseline Interferometry*, ed. M. Felli, R. E. Spencer (Dordrecht: Kluwer), p. 231

[9] Elitzur, M. 1992a, in Astronomical Masers (Dordrecht: Kluwer)
–. 1992b, ARA&Ap, 30, 75

[10] Gwinn, C. R., 1994, ApJ, 429, 241

[11] Imai, H., Morris, M., Sahai, R., Hachisuka, K., Azzollini, F. J. R. 2004, A&Ap, in press

[12] Imai, H., Horiuchi, S., Deguchi, S., Kameya, O. 2003, ApJ, 595, 285

[13] Imai, H., Shibata, K.M., Marvel, K.B., Diamond, P.J., Sasao, T., Miyoshi, M., Inoue, M., Migenes, V., Murata, Y. 2003, ApJ, 590, 460

[14] Imai, H., Obara, K., Diamond, P. J., Omodaka, T., & Sasao, T. 2002a, Nature, 417, 829

[15] Imai, H., Deguchi, S., Sasao, T. 2002b, ApJ, 567, 971

[16] Imai, H., Kameya, O., Sasao, T., Miyoshi, M., Deguchi, S., Horiuchi, S., Asaki, Y. 2000, ApJ, 538, 751

[17] Moran, J. M. Dhawan, V. 1995, in *Very Long Baseline Interferometry and the VLBA*, ed. J. A. Zens, P. J. Diamond, P. J. Napier (ASP: San Francisco), chap. 9

[18] Reid, M. J. 1999, in *Synthesized Imaging in Radio Astronomy II*, ed. G. B. Taylor, C. L. Carilli, R. A. Perley (ASP: San Francisco), chap. 24

[19] Reid, M. J. 1995, in *Very Long Baseline Interferometry and the VLBA*, ed. J. A. Zens, P. J. Diamond, P. J. Napier (ASP: San Francisco), chap. 11

[20] Reynolds, C., Paragi, Z., Garrett, M. A. 2002, in URSI General Assembly, Commission J (http://www.evlbi.org/pipeline/user_expts.html)

[21] Rupen, N. P. 1999, in *Synthesized Imaging in Radio Astronomy II*, ed. G. B. Taylor, C. L. Carilli, R. A. Perley (ASP: San Francisco), chap. 12

[22] Taylor, G. B., Carilli, C. L., Perley, R. A. 2001, Synthesized Imaging in Radio Astronomy II (ASP: San Francisco)

[23] Thompson, A. R., Moran, J. M., Swenson, G. W., Jr. 2001 in *Interferometry and Synthesis in Radio Astronomy, 2nd edition* (John Wiley & Sons: New York)

[24] Wajima, K. 2003, in *Radio Interferometry Summer School 2003*, chap. 15 (in Japanese)
—. 2004, translated in English.

[25] Walker, R. C. 1999, in *Synthesized Imaging in Radio Astronomy II*, ed. G. B. Taylor, C. L. Carilli, R. A. Perley (ASP: San Francisco), chap. 22

[26] Walker, R. C. 1995, in *Very Long Baseline Interferometry and the VLBA*, ed. J. A. Zens, P. J. Diamond, P. J. Napier (ASP: San Francisco), chap. 13

[27] Walker, C. R. 1981, AJ, 86, 1323

Appendix A

Appendices

A.1 Installation and setting AIPS

Instruction of AIPS installation is described in the NRAO's AIPS home page, `http://www.aoc.nrao.edu/aips/`. Therefore, the installation instruction is not described in this document. Some of special remarks are described as follows.

A.1.1 Disk space

A working disk space is recommended to be larger than 10 Gbytes per *observation*. Here one *observation* corresponds to data that consists of scans of one target source and calibrators for obtaining images or image cubes of the target source in one observing epoch, usually during shorter than 24 hours. Because spectral line (mainly maser) data have a large number of spectral channels and short parameter periods (see [2]), the data size easily gets huge. For example, the author is always getting VLBA data with a size as large as 15 Gbytes because the data are obtained from 10 antennas and have 1024 spectral channels. Therefore, DAT tape drives, with which DDS3 or DDS4 tapes are available, are necessary to put FITS data to hard disk drive (HDD) even if the files in HDD are compressed into 1/3 of the original size. Even VERA and KVN with smaller number of telescopes do not change such a situation because all of users may have data of multiple observations. Data size limit of 2 Gbytes also should be fixed by install the latest LINUX or UNIX operating system and by compiling AIPS programs in C and FORTRAN, which does not appear the data size limit.

A.1.2 Work permission

The administrator of your computer in your institutes should edit `/etc/services` to put the following lines.

```
sssin          5000/tcp        SSSIN      # AIPS TV server
ssslock        5002/tcp        SSSLOCK    # AIPS TV Lock
msgserv        5008/tcp        MSGSERV    # AIPS Message Server
tekserv        5009/tcp        TEKSERV    # AIPS TekServer
aipsmt0        5010/tcp        AIPSMT0    # AIPS remote FITS disk access
aipsmt1        5011/tcp        AIPSMT1    # AIPS remote tape 1
aipsmt2        5012/tcp        AIPSMT2    # AIPS remote tape 2
aipsmt3        5013/tcp        AIPSMT3
aipsmt4        5014/tcp        AIPSMT4
aipsmt5        5015/tcp        AIPSMT5
aipsmt6        5016/tcp        AIPSMT6
aipsmt7        5017/tcp        AIPSMT7
```

In addition, the administrator should permit AIPS user putting *RUN files* (see sections 1.4 and 17.2) in the directory `$AIPS_ROOT/RUN` or `$AIPS_ROOT/$AIPS_VERSION/RUN`, and *HELP files* (see section 17.2) in the directory `$AIPS_ROOT/$AIPS_VERSION/HELP`.

A.2   User environment for AIPS

It is convenient for a user to set the following environments and commands because the user may always have to type them before starting AIPS.

A.2.1   Commands in the login script

Add the following script either in `.login` or `.cshrc` (in c-shell environment), `.bashrc` (in bash-shell environment).

- In the case of c-shell environment: `source` *[AIPS_root directory]*`/LOGIN.CSH;$CDTST`

- In the case of bash-shell environment: `source` *[AIPS_root directory]*`/LOGIN.SH;$CDTST`

These enables the user to the default variables specified in AIPS. A user has to type them when he/she wants to touch AIPS programs themselves (e.g. when updating AIPS).

A.2.2   Special variables for user

For example, a user may want to specify a directory to put PostScript files created by AIPS. In this case, it is recommended to specify a directory to do it. The following command or script in the login script can set the directory.

- In the case of c-shell environment: `setenv` *[New variable name] [Your specified directory]*

- In the case of bash-shell environment: `export` *[New variable name]=[Your specified directory]*

A.3   Updating AIPS version

Updating AIPS version is essential for smoothly operating AIPS. Some of AIPS tasks may have severe bugs. There may be many problems just after installing newer version of AIPS. To update the AIPS version, a user should perform the following procedures.

- Log in as an AIPS administrator, or a login user to install/update AIPS.

- Type the scripted described in chapter A.2.1.

- Move to the home directory of the AIPS administrator. The script named `do_diary.`*[host name]*.

- Type `source do_diary.`*[host name]*.

- Move to `$UPDATE` and look at the file named `UPD`*[date]*. *[time]*. The date and time are the epoch when AIPS was updated by using the above script. This output file is a log file to record what parts were updated in AIPS.

- In AIPS, type `RUN NEWPARAM`.

A.4   About this document

- 22 March 2004: 1st version.

- 25 March 2004: 2nd version, many modifications and additions.

- 5 May 2004: 3rd version, updating chapter 1 and appendix.

- 4 June 2004: 4rd version, improving several figures.

- 26 October 2005: 5rd version, improving several figures and documents.