

KOMB OUTPUT FILE FORMAT  
and  
ITEMS OUTPUT TO DATABASE

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## Contents

<b>1</b>	<b>KOMB (band width synthesis) output data format (Ver.2018-06-14)</b>	<b>1</b>
1.1	Header record (HD) . . . . .	2
1.2	Observation and correlation information record (OB) . . . . .	3
1.3	Band-width synthesis result record (BD) . . . . .	4
1.4	Type500 record (5R) . . . . .	7
1.5	Type600 record(6R) (cross spectrum and phase and delay correction information for WBWS mode) . . . . .	8
<b>2</b>	<b>Items output to data base</b>	<b>10</b>

# 1 KOMB (band width synthesis) output data format (Ver.2018-06-14)

KOMB (band-width synthesis software package) processes a correlator output data file of which name starts from either “K” or “C” or “E”<sup>1</sup> and creates an output file having the name as same as that of correlator output file but the 1st character is substituted by “B” (means KOMB output file). If KOMB output file has been already existed, processing results are appended to the file. The place where KOMB outputs a file follows a rule below. If letter string “kross” is included in the pass of correlator output file, the pass (directory) of which letter string “kross” substituted by “komb” will become the pass for KOMB output file. For an example, KOMB processes correlator output file “/vlbdata1/kross1/KS97123/K01234” and creates KOMB output file “/vlbdata1/komb1/KS97123/B01234”. Therefore, the corresponding directory for KOMB output files should be created in advance. If there is no letter string “kross” in the pass of correlator output file, KOMB outputs results to the same directory as that of correlator output file.

KOMB output file consists of 256-byte fixed-length records, and each record is classified into 5 kinds as follows; header record (HDxx: xx is serial number), observation and correlation information record (OBxx), band-width synthesis result record (BDxx), correlation amplitude and phase by PP record (5R), and line printer image record (#1 and #2). BD, 5R, #1, and #2 records are appended when KOMB processes the same correlation data file.

HD	OB	BD	5R	#1	#2	6R	BD	5R	#1	#2	6R	BD	...
----	----	----	----	----	----	----	----	----	----	----	----	----	-----

Figure 1: Contents of KOMB output file. HD: header record, OB: observation and correlation information record, BD: band-width synthesis result record, 5R: correlation amplitude and phase by PP record, #1 and #2: line printer image record. 6R: cross spectrum record when WBWS processing with ‘-SPE’ option.

HD00	HD01	...		
OB01	OB02	OB03		
BD01	BD02	BD03	BD04	BD05
5R	5\$	5\$	...	
#1	ASCII data	ASCII data	...	
#2	ASCII data	ASCII data	...	
6R	6\$	6\$	...	

Figure 2: Contents of each record, i.e., HD, OB, BD, 5R, #1, #2 from top to bottom. Each record is a 256-byte fixed-length record.

<sup>1</sup>“K”: KSP correlator output format, “C”: software correlator output format (converted from ‘cout’ format to KSP format), “E”: extended KSP format which is free from the limit of lags

1.1 Header record (HD)

mnemonic	# of bytes	byte position	type	comment
LID	4	1	A4	record ID (4 letters) "HDxx" xx denotes continuation, 00, 01, ...
KSPID	3	5	A3	KSP format ID (3 letters) "KSP"
—	1	8	—	unused
EXCODE	10	9	A10	experiment code (10 letters)
NOBS	2	19	I*2	observation number
LBASE	2	21	A2	baseline ID (2 letters)
LREC	2	23	I*2	total number of records in this file
LHDCN	2	25	I*2	total number of HD records
LFILB	6	27	A6	KOMB output file nme (6 letters)
—	24	33	—	unused
... directory of record ID ...				
[Record #1]				
	2	57	I*2	record #
	4	59	A4	record ID (4 letters) ("T500" for Type 500 record that has no record ID)
	2	63	A2	frequency sub-group ID of the record (2 letters) ("X" or "S" or "W". " " (two spaces) for header record block)
.				
.				
repeat directory of record ID up to 25 times.				
If total number of records exceed 25, header record is repeated so as to include all record information.				
.				
.				
[Record #25]				
	2	57	I*2	record #
	4	59	A4	record ID (4 letters) ("T500" for Type 500 record that has no record ID)
	2	63	A2	frequency sub-group ID of the record (2 letters) ("X" or "S" or "W". " " (two spaces) for header record block)

## 1.2 Observation and correlation information record (OB)

mnemonic	# of bytes	byte position	type	comment
LID	4	1	A4	record ID (4 letters) "OB01"
—	4	5	—	unused
EXCODE	10	9	A10	experiment code (10 letters)
NOBS	2	19	I*2	observation number
LBASE	2	21	A2	baseline ID (2 letters)
IOBSST	10	23	I*2	DIM(5) Observation (scan) start time (year, total day, hour, minute, second)
IOBSET	10	33	I*2	DIM(5) Observation(scan) stop time (year, total day, hour, minute, second)
IPRT	10	43	I*2	DIM(5) PRT (Processing Reference Time) (year, total day, hour, minute, second)
LCROSS	6	53	A6	correlator output file name (6 letters)
—	2	59	—	unused
LFILB5	6	61	A6	KOMB output file name
—	2	67	—	unused
KRDATE	8	69	I*2	DIM(4) correlation procesing time (year, total day, hour, minute)
—	4	77	—	unused
NPPSEC	2	81	I*2	PP period (sec)
NPP	2	83	I*2	# of PP
SAMPL	4	85	R*4	sampling period (sec)
VBW	4	89	R*4	video band width (Hz)
LMODE	2	93	A2	correlator mode "NO": normal mode, "SE": fringe search mode
LSORNA	8	95	A8	radio source name (8 letters)
SDEC	4	103	R*4	declination of radio source (deg) J2000
SGHA	4	107	R*4	Greenwich hour angle of the source at PRT (deg)
LSTATX	8	111	A8	X station name (8 letters)
LSTATY	8	119	A8	Y station name (8 letters)
DXXYZ	24	127	R*8	DIM(3) X station position (x, y, z) (m)
DYXYZ	24	151	R*8	DIM(3) Y station position (x, y, z) (m)
DTAUAP	32	175	R*8	DIM(4) a-priori values at PRT at correlation processing $\tau$ (sec), $\dot{\tau}$ (s/s), $\ddot{\tau}$ (s/s <sup>2</sup> ), and $\dddot{\tau}$ (s/s <sup>3</sup> )
DACLKE	8	207	R*8	a-priori clock error (sec) time synchronization error between X and Y stations at PRT (positive sign denotes that Y clock is ahead)
DACLKR	8	215	R*8	clock rate difference between X and Y stations at PRT (s/s)
DLYINS	8	223	R*8	instrumental delay difference between X and Y stations (sec)
DXCLKE	8	231	R*8	difference between X station clock and UTC at PRT (sec)
SRA	4	239	R*4	right ascension of the radio source (deg) J2000
FMTFLAG	4	243	A4	unused or flag to identify format as follows. "KSP <sub>L</sub> "   "K4 <sub>L</sub> "   "KSP1"   "KSP2" The unit of PP is sec for "KSP <sub>L</sub> " and "K4 <sub>L</sub> ", 10 msec for "KSP1", and 1 msec for "KSP2".
—	14	247	—	unused

mnemonic	# of bytes	byte position	type	comment
LID	4	1	A4	record ID (4 letters) "OB02"
—	4	5	—	unused
DPI	8	9	R*8	$\pi$
DCV	8	17	R*8	light speed (m/s)
EOPFLAG	2	25	A2	EOP flag (always "ON")
UT1_C	4	27	R*4	UT1-UTC (sec)
XWOBB	4	31	R*4	Wob-X (arcsec)
YWOBB	4	35	R*4	Wob-Y (arcsec)
—	18	39	—	unused
NFREQA	2	57	I*2	total number of channels processed
INDEXT	64	59	I*2	DIM(2,16) index number table (by side band (USB, LSB), by channel)
—	134	123	—	unused

mnemonic	# of bytes	byte position	type	comment
LID	4	1	A4	record ID (4 letters) "OB03"
—	4	5	—	unused
DFREQT	128	9	R*8	DIM(16) RF frequency table (Hz) by channel
PCALFX	64	137	R*4	DIM(16) X station PCAL frequency table (Hz) (by channel)
—	56	201	—	unused

### 1.3 Band-width synthesis result record (BD)

mnemonic	# of bytes	byte position	type	comment
LID	4	1	A4	record ID (4 letters) "BD01"
BWSMOD	4	5	A4	unused or "EBWS" that denotes extended band-width synthesis or "WBWS" that denotes wide band band-width synthesis
IDSUB	2	9	A2	frequency sub-group ID (2 letters) "X" or "S" or "W"
KMDATE	8	11	I*2	KOMB processing date and time (year, total day, hour, minute)
KOMVAL	2	19	I*2	KOMB processing number =(KROSS processing number) $\times$ 1000+(KOMB processing number)
ISTART	12	21	I*2	DIM(6) correlation data start time (year, total day, hour, minute, second, milli-second)
ISOP	12	33	I*2	DIM(6) correlation data stop time (year, total day, hour, minute, second, milli-second)
NFREQ	2	45	I*2	total number of channels processed
INDEX	64	47	I*2	DIM(2,16) index number table (by sideband (USB, LSB), by channel)
NTAPEQ	6	111	A6	tape quality code (6 letters) (no meaning in KSP system)
DRREF	8	117	R*8	processing reference RF frequency (Hz)
DRFREQ	128	125	R*8	DIM(16) RF frequency table (Hz)
IONFLG	4	253	A4	unused or flag to TEC estimation (4 characters) "OFF□":no estimation, "ONmw": estimation ("GTEC" for given TEC) where 'm' is 1 2 3 showing an estimation method, and 'w' is 0 1 2 showing a weighting mode.

mnemonic	# of bytes	byte position	type	comment
LID	4	1	A4	record ID (4 letters) "BD02"
BWSMOD	4	5	A4	unused or "EBWS" that denotes extended band-width synthesis or "WBWS" that denotes wide band band-width synthesis
IDSUB	2	9	A2	frequency sub-group ID (2 letters) "LX" or "LS" or "LW"
KOMBQ	2	11	A2	KOMB quality code
JERRS	80	13	A4	DIM(20) error status mask code (4 letters) × 20
NPPR	64	93	I*2	DIM(2,16) processing PP number table (by sideband, by channel)
QB	4	157	R*4	rms PP number by channel
TEF	4	161	R*4	effective integration period (sec)
FISC	4	165	R*4	rejection rate of correlation data
IEPOCM	12	169	I*2	DIM(6) central epoch (center time of processing data) (year, total day, hour, minute, second, milli-second)
DGPDM	8	181	R*8	observed group delay at the central epoch (sec)
DRATM	8	189	R*8	observed delay rate at the central epoch (s/s)
TOTPM	4	197	R*4	observed total phase at the central epoch (deg)
SSDES	8	201	R*4	DIM(2) coarse delay search parameters (start, stop) (really used values: sec)
SMDEM	8	209	R*4	DIM(2) fine delay search parameters (start, stop) (really used values: sec)
SRTM	8	217	R*4	DIM(2) fine delay rate search parameters (start, stop) (really used values: s/s)
DEPE	8	225	R*8	PRT – earth centered epoch (sec)
TOTP	4	233	R*4	observed total phase at PRT (deg)
EARP	4	237	R*4	observed total phase at the earth centered epoch (deg)
REARP	4	241	R*4	observed residual fringe phase at the earth centered epoch (deg)
TEC	8	245	R*8	unused or ionospheric correction $\Delta TEC$ (electrons/m <sup>2</sup> ) for WBWS mode. When TEC is given from the outside, i.e., IONFLG="GTEC" in the BD01 record, its value.
TECERR	4	253	R*4	unused or estimation error of TEC

mnemonic	# of bytes	byte position	type	comment
LID	4	1	A4	record ID (4 letters) "BD03"
BWSMOD	4	5	A4	unused or "EBWS" that denotes extended band-width synthesis or "WBWS" that denotes wide band band-width synthesis
IDSUB	2	9	A2	frequency sub-group ID (2 letters) "LX" or "LS" or "LW"
DRPCAL	16	11	R*8	DIM(2) PCAL rate (s/s) by station (X, Y)
XAPCAL	128	27	R*4	DIM(2,16) X station PCAL amplitude and phase (deg) table
PCFILE	102	155	A80	unused or phase correction file name for EBWS or WBWS mode. "NONE" means that no phase correction at EBWS or WBWS mode
PCFPRT	10	235	I*2	unused or PRT (yyyy, ddd, hh, mm, ss) of the scan that used for making the PCFILE file
—	11	245	—	unused

mnemonic	# of bytes	byte position	type	comment
LID	4	1	A4	record ID (4 letters) "BD04"
BWSMOD	4	5	A4	unused or "EBWS" that denotes extended band-width synthesis or "WBWS" that denotes wide band band-width synthesis
IDSUB	2	9	A2	frequency sub-group ID (2 letters) "LX" or "LS" or "LW"
—	16	11	—	unused
YAPCAL	128	27	R*4	DIM(2,16) X station PCAL amplitude and phase (deg) table
DCFILE	102	155	A80	unused or inter-band delay correction file name for WBWS mode. "NONE" means that no inter-band delay correction at WBWS
DCFPRT	10	235	I*2	unused or PRT (yyyy, ddd, hh, mm, ss) of the scan that used for making the DCFILE file
—	11	245	—	unused

mnemonic	# of bytes	byte position	type	comment
LID	4	1	A4	record ID (4 letters) "BD05"
BWSMOD	4	5	A4	unused or "EBWS" that denotes extended band-width synthesis or "WBWS" that denotes wide band band-width synthesis
IDSUB	2	9	A2	frequency sub-group ID (2 letters) "LX" or "LS" or "LW"
COHE	4	11	R*4	fine search fringe amplitude
AAMP	4	15	R*4	coarse search fringe amplitude
SNR	4	19	R*4	SNR
AICOH	4	23	R*4	incoherently integrated fringe amplitude
PROB	4	27	R*4	false detection probability for fringe peak
DGPD	8	31	R*8	observed fine search group delay at PRT (sec)
DTAU	8	39	R*8	observed fine search group delay residual (sec) = (delay residual obtained by fine search only)
EGPD	4	47	R*4	one sigma error of observed fine search group delay (sec)
GPDA	4	51	R*4	ambiguity of fine search group delay (sec)
DRATO	8	55	R*8	observed delay rate at PRT (s/s) (after PCAL rate correction)
DRATR	8	63	R*8	observed delay rate residual (s/s) = (coarse search delay rate residual) + (fine search delay rate residual) (without PCAL rate correction)
ERAT	4	71	R*4	one sigma error of observed delay rate (s/s)
DGPDN	8	75	R*8	observed coarse delay at PRT (sec)
DTAUS	8	83	R*8	coarse search delay residual (sec)
EGPDN	4	91	R*4	one sigma error of coarse search delay (sec)
DRATS	8	95	R*8	coarse search delay rate residual (s/s)
DPHD	8	103	R*8	phase delay (sec) at PRT
DPHD1	8	111	R*8	phase delay (sec) at PRT+1 sec
DPHD2	8	119	R*8	phase delay (sec) at PRT-1 sec
AMPB	128	127	R*4	DIM(2,16) fringe amplitude and phase (deg) by channel
—	2	255	—	unused



## 1.4 Type500 record (5R)

mnemonic	# of bytes	byte position	type	comment
LID2	2	1	A2	record ID (2 letters) "5R" or "5\$" for continuation
IDUR	2	3	I*2	continuation number
INDEXN	4	5	I*2	DIM(2) index # for this PP data by sideband
OBSPTM	4	9	R*4	time at the first data of each block (10 second value past from on the hour)
PPTIM	4	13	R*4	PP period (sec)
EPCOTM	4	17	R*4	time at the first data of each block (10 second value past from PRT)
—	36	21	—	unused
	2	57	I*2	amplitude at the 1st PP (normalized as 30000=100%) -1 = deleted or no data -2 = just to fill out (initialized data)
	2	59	I*2	phase at the 1st PP 0 ~ 9999 = 0 ~ 360° USB+LSB 10000 ~ 19999 = 0 ~ 360° USB 20000 ~ 29999 = 0 ~ 360° LSB phase means residual phase after KROSS+KOMB processing PCAL rate is not corrected -1 = deleted or no data -2 = jsut to fill out (initialized data)
	2	61	I*2	X PCAL signal phase at the 1st PP
	2	63	I*2	Y PCAL signal phase at the 1st PP 0 ~ 9999 = 0 ~ 360° -1 = deleted or no data -2 = jsut to fill out (initialized data)
				... repeat items from byte position 57 to 63 up to 25 times ...
	2	255	I*2	Y PCAL signal phase at the 25th PP

mnemonic	# of bytes	byte position	type	comment
LID2	2	1	A2	record ID (2 letters) "#1". header record of PLOT#1
NREC	2	3	I*2	# of records (NREC records of line-printer image data follows this record)
—	252	5	—	unused

mnemonic	# of bytes	byte position	type	comment
LID2	2	1	A2	record ID (2 letters) "#2". header record of PLOT#2
NREC	2	3	I*2	# of records (NREC records of line-printer image data follows this record)
—	252	5	—	unused

### 1.5 Type600 record(6R) (cross spectrum and phase and delay correction information for WBWS mode)

mnemonic	# of bytes	byte position	type	comment
LID2	2	1	A2	record ID ( 2 letters) "6R" or "6\$" for continuation.
IDUR	2	3	I*2	continuation number
NUMDAT	4	5	I*4	# of spectrum elements
PHSOFST	4	9	R*4	phase offset (deg) (applied for all data)
	6	13	-	unused
	8	19	R*8	RF frequency (Hz) 0.0 = jsut to fill out
	2	27	I*2	band INDEX # 0 = jsut to fill out
	4	29	R*4	cross spectrum (real part)
	4	33	R*4	cross spectrum (imaginary part)
	4	37	R*4	phase correction data in a band (deg)
	4	41	R*4	phase correction data inter band (deg)
	8	45	R*8	delay correction data inter band (sec)
				... repeat items 19~52 upto 7 times ...
	8	249	R*8	7th delay correction data inter band (sec)

**Update history**

**2018.06.14** Add EOP parameters to “OB02” record

**2016.04.20** modify IONFLAG in “BD01” record

**2016.02.16** modify BWASMOD in BD records. modify IONFLG in “BD01” record and TEC in “BD02” record.

**2015.10.13** add correction data file names and epoch information to “BD03” and “BD04” records.

**2015.10.07** add TEC estimation flag to “BD01” record.

**2015.08.05** add TEC estimation error to “BD02” record.

**2015.03.02** add Type600 records to output cross spectrum in case of WBWS mode with ‘-SPE’ option.

**2015.02.25** Add new mode “WBWS”<sup>1</sup> in BWSMOD field in BDxx records to support a wide-band band width synthesis. Frequency group (SUBID) of “□W” was newly defined for the WBWS mode, and some items were added to reflect a WBWS mode processing.

**2014.08.26** Add new field “FMTFLAG” in the OB01 record according to the addition of “KSP2” mode in FMTFLAG field in the correlator output data.

**2012.01.12** Support extended band-width synthesis (EBWS)<sup>2</sup> processing. Information showing EBWS processing was added to BDxx records.

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<sup>1</sup>WBWS was developed to process a wide-band band width synthesis of which band width is wider than the case of EBWS.

<sup>2</sup>EBWS was developed to process RF-direct sampling data and do band-width synthesis for a number of band data without band gap.

## 2 Items output to data base

Items output to the data base are summarized here.

1. **KOMB processing date** ... Date and time obtained from a PC when KOMB executes.
2. **KOMB processing number** ... The number of KOMB processings for correlator output data, which is incremented by processing the same data.
3. **RF reference frequency** ... Reference frequency is the frequency representing the frequency group processed by KOMB. Lowest frequency among channels processed is usually assigned as the reference frequency unless an operator compulsory sets it.
4. **Processing track number table** ... Recorder track number of correlation data. Valid only for K3/Mark-III system.
5. **Effective integration period** ... Integration period averaged over channels.

$$TEF = \frac{\text{total number of PPs} \times T_{pp}}{\text{total number of channels}}$$

where  $T_{pp}$  denotes the period of PP (Parameter Period).

6. **Central epoch (EPOCM)** ... Time (UTC) representing the center of correlated data processed by KOMB. *EPOCM* is calculated as follows,

$$EPOCM = UTC_{PP\#1} + \frac{1}{N} \left[ \sum_{n=1}^N \left\{ \frac{\sum_{k=1}^K d_n(k) \cdot (k \cdot T_{pp} - \frac{1}{2}T_{pp})}{K} \right\} \right]$$

where

$$\begin{aligned} K & : \text{total number of PP} \\ UTC_{PP\#1} & : \text{time (UTC) of the X station at the 1st PP data} \\ N & : \text{total number of channels} \\ T_{pp} & : \text{period of PP} \\ d_n(k) & = \begin{cases} 1 \cdots & \text{when KOMB uses n-th channel, k-th PP data for processing} \\ 0 \cdots & \text{when KOMB discards this PP data} \end{cases} \end{aligned}$$

7. **Processing PP number by sideband, by channel (NPPK(2,N))** ... PP number table used for KOMB processing by sideband and by channel. The table includes discarded number of PPs at processing.
8. **PCAL amplitude and phase by station, by channel (APCAL(2,2,N))** ... PCAL amplitude and phase table by station and by channel. As for the K3 correlator output, PCAL phase for Y-station is corrected as follows.

$$\begin{aligned} AR & = \sum_{k=1}^K \{a(k) \cdot \cos \theta_k + b(k) \cdot \sin \theta_k\} \\ AI & = \sum_{k=1}^K \{b(k) \cdot \cos \theta_k - a(k) \cdot \sin \theta_k\} \cdot SB \end{aligned}$$

where

$$\begin{aligned} K & : \text{total number of PP processed} \\ a(k) & : \text{real part of normalized PCAL amplitude for k-th PP} \\ b(k) & : \text{imaginary part of normalized PCAL amplitude for k-th PP} \end{aligned}$$

$$\theta_k = \begin{cases} 0 \cdots & \text{for X station} \\ 2\pi \cdot F_{cal} \Delta T_{XY} \cdots & \text{for Y station} \end{cases}$$

$F_{cal}$  : PCAL frequency  
 $\Delta T_{XY}$  : time offset (bit offset) of Y data stream against X data stream  
 $> 0$  means X data time behind Y data time

$$SB = \begin{cases} 1 \cdots & \text{USB} \\ -1 \cdots & \text{LSB} \end{cases}$$

This correction is no more necessary for KSP and modern correlator output. Using  $AR$ ,  $AI$  PCAL phase  $\phi_{cal}$  and amplitude  $A_{cal}$  are calculated as

$$\phi_{cal} = \tan^{-1} \left( \frac{AI}{AR} \right)$$

$$A_{cal} = \frac{1}{K} \sqrt{AR^2 + AI^2}$$

**9. Tape error rate by station, by track (ERTPE)**  $\cdots$  Parity error rate table of data by station and by track defined as follows.

$$ER(S, Tr) = \frac{\sum_{k=1}^K PE_k(S, Tr)}{K \cdot B_{PP}}$$

where

- $S$  : station index
- $Tr$  : track index
- $PE_k(S, Tr)$  : parity error count value for  $S, Tr$  at PP# k
- $K$  : total number of PP
- $B_{PP}$  : number of bytes in PP

Note that Mark-III adopts the value calculated by  $1000 \log(ER)$  for data base. ERTPE has no meaning for modern VLBI system.

**10. PCAL rate by station (RPCAL)**  $\cdots$  PCAL rate is calculated from PCAL data by PP as follows,

$$1. \quad D(J) = \sum_{n=1}^N \cdot \sum_{k=1}^K \exp\{i(\phi_n(k) - \overline{\phi_n} - \omega_0^n \cdot R_J \cdot T_{PP} \cdot (k-1))\}$$

where

- $N$  : total number of channels
- $\phi_n(k)$  : PCAL phase at PP#=k and frequency channel=n
- $\overline{\phi_n}$  : averaged PCAL phase for channel n
- $\omega_0^n$  : RF angular frequency for channel n
- $R_J = \begin{cases} -\Delta\dot{\tau} & \text{for } J = 1 \\ 0 & \text{for } J = 2 \\ +\Delta\dot{\tau} & \text{for } J = 3 \end{cases} \quad \Delta\dot{\tau} : \text{search step in } \dot{\tau} \text{ direction}$

2. compute  $D(1)$ ,  $D(2)$ ,  $D(3)$ , then find out a point that maximizes  $|D|$  by using a parabola fit. let this point be  $A$  and amplitude be  $D'(2)$ .
3.  $|D|$  at two points separated from the point  $A$  by  $\pm \Delta\dot{\tau}/2$  (let them be  $D'(1)$  and  $D'(3)$ ), do a parabola fit again, then obtain RPCAL that maximize  $|D|$ .  $D'(1)$ ,  $D'(2)$ , and  $D'(3)$  are calculated by setting  $R_J$  in 1. as follows,

$$R_J = \begin{cases} A - \frac{1}{2}\Delta\dot{\tau} & J = 1 \\ A & J = 2 \\ A + \frac{1}{2}\Delta\dot{\tau} & J = 3 \end{cases}$$

Process 1., 2., 3. for X and Y station data.

11. **Discarded data rate (DISC)** ... The ratio of the number of PPs really used for KOMB processing to total number of PPs.

$$DISC = \frac{\text{number of PPs really used for KOMB processing}}{\text{total number of PPs}}$$

12. **Group delay at PRT (GPD)** ... Observed group delay after band-width synthesis. Ambiguities caused by the band-width synthesis are corrected as follows,

$$GPD = \tau_{ap} + \Delta\tau_m + t_{amb} \cdot \text{rint} \left( \frac{\Delta\tau_s}{t_{amb}} \right)$$

where  $\tau_{ap}$ ,  $\Delta\tau_s$ ,  $t_{amb}$ , and  $\Delta\tau_m$  are a-priori delay, residual delay obtained by a coarse search, ambiguity at band-width synthesis, and delay residual obtained by a fine search, respectively, and  $\text{rint}$  is a function returning the nearest integer. The third term of right-hand side of the equation is correction to reflect the ambiguity. This term can be zero because the ambiguity will be adjusted later at a baseline-analysis phase.

13. **Error of group delay (EGPD)** ... Theoretical value of the one sigma error of observed group delay calculated as follows,

$$EGPD = \sigma_\tau = \frac{1}{\Delta\omega_{rms} \cdot SNR}$$

where

$$\Delta\omega_{rms} = \sqrt{\frac{1}{N} \sum_{n=1}^N (\omega_n - \bar{\omega})^2}$$

$$\bar{\omega} = \frac{1}{N} \sum_{n=1}^N \omega_n$$

$N$  : total number of channels

$\omega_n$  : RF angular frequency of n-ch

when processing number of channels is only 1

$$\Delta\omega_{rms} = \frac{\omega_B}{\sqrt{12}} \quad \omega_B : \text{video band-width}$$

$$SNR = \frac{2}{\pi} \rho_0 \sqrt{K}$$

$K$  : total number of bits (samples) processed

$\rho_0$  : correlation amplitude

14. **Ambiguity of group delay obtained by band-width synthesis (GPDA)** ... Let the greatest common denominator of the space of frequency allocation for band-width synthesis be  $FS$ , ambiguity is the inverse of  $FS$ , i.e.,

$$GPDA = \frac{1}{FS}$$

15. **Coarse search delay at PRT (GPDN)** ... GPDN is given as

$$GPDN = \tau_{ap} + \Delta\tau_s$$

where  $\tau_{ap}$  is a-priori delay and  $\Delta\tau_s$  is residual delay obtained by a coarse search.

16. **Error of coarse search delay (EGPDN)** ... Theoretical one sigma error is calculated as follows,

$$EGPDN = \frac{\sqrt{12}}{\omega_B \cdot SNR}$$

where

$$\begin{aligned} \omega_B & : \text{video band-width} \\ SNR & = \frac{2}{\pi} \rho_0 \sqrt{K} \\ & K : \text{total number of bits (samples) processed} \\ & \rho_0 : \text{correlation amplitude} \end{aligned}$$

**17. Observed delay rate at PRT (RAT)** ... RAT is calculated as follows,

$$RAT = \dot{\tau}_{ap} + \Delta\dot{\tau}_s + \Delta\dot{\tau}_m + (\text{X PCAL rate}) - (\text{Y PCAL rate})$$

where  $\dot{\tau}_{ap}$ ,  $\Delta\dot{\tau}_s$ , and  $\Delta\dot{\tau}_m$  are a-priori delay rate, delay-rate residual obtained by a coarse search, and delay-rate residual obtained by a fine search, respectively.

**18. Error of observed delay rate (ERAT)** ... ERAT is the theoretical one sigma error of observed delay rate and is calculated as

$$ERAT = \sqrt{\frac{12}{\omega^2}} \cdot \frac{1}{T \cdot SNR}$$

where

$$\begin{aligned} \overline{\omega^2} & = \frac{1}{N} \sum_{n=1}^N \omega_n^2 \\ N & : \text{total number of channels} \\ T & : \text{integration period (sec)} \cdots \text{use effective integration period (TEF)} \\ SNR & = \frac{2}{\pi} \rho_0 \sqrt{K} \\ & K : \text{total number of bits (samples) processed} \\ & \rho_0 : \text{correlation amplitude} \end{aligned}$$

**19. Phase delay at PRT (PHD)** ... PHD is calculated as follows,

$$PHD = \tau_{ap} + \frac{\Phi}{\omega_{ref}}$$

where

$$\begin{aligned} \tau_{ap} & : \text{a-priori delay at PRT} \\ \Phi & : \text{phase of } D(\Delta\tau_m, \Delta\dot{\tau}_m) \\ & \text{where } \Delta\tau_m \text{ is delay residual obtained by a fine search} \\ & \text{and } \Delta\dot{\tau}_m \text{ is delay-rate residual obtained by a fine search} \\ \omega_{ref} & : \text{RF angular frequency} \end{aligned}$$

(1)

and  $D(\Delta\tau_m, \Delta\dot{\tau}_m)$  is defined as

$$D(\Delta\tau_m, \Delta\dot{\tau}_m) = \sum_{n=1}^N \left[ \exp\{-i(\omega_0^n \Delta\tau_m + \Delta\phi_n)\} \cdot \sum_{k=1}^K D_s(n, k) \cdot \exp(-i\omega_0^n \Delta\dot{\tau}_m \cdot T_{pp} \cdot k) \right]$$

where

$$\begin{aligned} \omega_0^n & : \text{RF angular frequency for n-ch} \\ \Delta\phi_n & : \text{PCAL phase difference} \\ D_s & : \text{single band delay resolution function (see 28.)} \\ k & : \text{PP index} \\ K & : \text{total number of PPs} \\ N & : \text{total number of channels} \end{aligned}$$

**20. Phase delay at PRT+1 sec (PHD1)** ... PHD1 is calculated as

$$PHD1 = PHD + RAT + \frac{1}{2}\ddot{\tau}_{ap}$$

where  $PHD$ ,  $RAT$  are observed phase delay and delay rate at PRT, and  $\ddot{\tau}_{ap}$  is a-priori delay acceleration (second derivative of delay) at PRT.

**21. Phase delay at PRT-1 sec (PHD2)** ... Similar to PHD1, PHD2 is calculated as

$$PHD1 = PHD - RAT + \frac{1}{2}\ddot{\tau}_{ap}$$

where  $PHD$ ,  $RAT$  are observed phase delay and delay rate at PRT, and  $\ddot{\tau}_{ap}$  is a-priori delay acceleration (second derivative of delay) at PRT.

[Note]

In Mark-III system a-priori delays are directly calculated at PRT+1 sec and at PRT-1 sec, then PHD1 and PHD2 are obtained as follows,

$$\begin{aligned} PHD1_{(Mark-III)} &= \tau_{ap2} + \Delta\dot{\tau} & \text{where } \tau_{ap2} : \text{a-priori delay at PRT+1 sec} \\ PHD2_{(Mark-III)} &= \tau_{ap3} - \Delta\dot{\tau} & \tau_{ap3} : \text{a-priori delay at PRT-1 sec} \end{aligned}$$

where  $\Delta\dot{\tau}$  is observed delay rate at PRT.

**22. Total phase at PRT (TOTP)** ... TOTP is the sum of a-priori fringe phase at reference RF frequency and  $\Phi$  given by item "19. Phase delay at PRT (PHD)", i.e.,

$$TOTP = amod(\omega_{ref} \cdot \tau_{ap} + \Phi, 2\pi)$$

where  $amod(a, b)$  is the function returning residual when  $a$  is divided by  $b$ .

**23. Group delay at central epoch (GPDM)** ... GPDM is calculated from GPD (group delay at PRT) by shifting the epoch using the a-priori second time derivative of delay  $\ddot{\tau}_{ap}$  as follows,

$$GPDM = GPD - \Delta t \cdot RAT + \frac{1}{2}\Delta t^2 \cdot \ddot{\tau}_{ap}$$

where

$$\begin{aligned} \Delta t &= PRT - EPOCM & (EPOCM : \text{central epoch}) \\ GPD &: \text{observed group delay at PRT} \\ RAT &: \text{observed delay rate at PRT} \end{aligned}$$

[Note]

In Mark-III system, a-priori delay at the central epoch  $\tau_{apM}$  is computed from a model, then GPDM is calculated by using residual delay  $\Delta\tau$  and residual delay rate  $\Delta\dot{\tau}$  at PRT as follows,

$$GPDM_{(Mark-III)} = \tau_{apM} + \Delta\tau - \Delta\dot{\tau} \cdot (PRT - EPOCM)$$

**24. Delay rate at the central epoch (RATM)** ... RATM is calculated from RAT by shifting the epoch using the a-prioris upto the third time derivative of delay,  $\ddot{\tau}_{ap}$ , as follows,

$$RATM = RAT - \Delta t \cdot \ddot{\tau}_{ap} + \frac{1}{2}\Delta t^2 \cdot \ddot{\tau}_{ap}$$

where

$$\begin{aligned} \Delta t &= PRT - EPOCM & (EPOCM : \text{central epoch}) \\ RAT &: \text{observed delay rate at PRT} \\ \ddot{\tau}_{ap} &: \text{the third time derivative of the a-priori delay} \end{aligned}$$



[Note]

In Mark-III system, a-priori delay rate at the central epoch  $\dot{\tau}_{apM}$  is computed from a model, then RATM is calculated by using residual delay rate  $\Delta\dot{\tau}$  at PRT as follows,

$$RATM_{(Mark-III)} = \dot{\tau}_{apM} + \Delta\dot{\tau}$$

- 25. Total phase at the central epoch (TOTPM)** ... TOTPM is calculated by using a-priori delay at PRT and phase delay at PRT  $\Phi$  as follows,

$$TOTPM = amod(\omega_{ref} \cdot \tau_{apM} + \Phi - \omega_{ref} \cdot \Delta\dot{\tau} \cdot \Delta t, 2\pi)$$

where

$$\begin{aligned} \omega_{ref} & : \text{reference RF angular frequency} \\ \tau_{apM} & = \tau_{ap} - \Delta t \cdot \dot{\tau}_{ap} + \frac{1}{2} \Delta t^2 \cdot \ddot{\tau}_{ap} \\ \Delta t & = PRT - EPOCM \quad (EPOCM : \text{central epoch}) \\ \Phi & : \text{observed residual total phase} \\ \Delta\dot{\tau} & = \Delta\dot{\tau}_s + \Delta\dot{\tau}_m \quad : \text{total residual } \dot{\tau} \text{ obtained by coarse and fine searches} \end{aligned}$$

[Note]

In Mark-III system,  $\tau_{apM}$  is computed at the central epoch from a model.

- 26. Total phase at the earth centered epoch (EARP)** ... Earth centered epoch (ECPRT) is defined as the time when a wave-front passing through the X-station at PRT passes the earth center and calculated as follows,

$$ECPRT = PRT - \frac{1}{c}(\vec{S} \cdot \vec{e})$$

where

$$\begin{aligned} \vec{S} & : \text{X-station position vector from the earth center} \\ \vec{e} & : \text{unit source vector from the earth center} \\ c & : \text{light velocity} \end{aligned}$$

Let the right-handed Cartesian coordinate of X-station be  $(S_x, S_y, S_z)$ , then

$$\vec{S} = (S_x, S_y, S_z)$$

Let the declination and the Greenwich hour angle of radio source be  $\delta$  and  $H$ , then

$$\vec{e} = (\cos \delta \cos H, -\cos \delta \sin H, \sin \delta)$$

Hence, ECRPT is also calculated as follows,

$$ECPRT = PRT - \frac{1}{c} \{S_z \sin \delta + \cos \delta (S_x \cos H - S_y \sin H)\}$$

EARP is calculated from TOTP by shifting the epoch by using ECPRT as follows,

$$EARP = amod(TOTP - \Delta T_c \cdot RAT \cdot \omega_{ref}, 2\pi)$$

where

$$\begin{aligned} TOTP & : \text{total phase at PRT} \\ \Delta T_c & = PRT - ECPRT \\ RAT & : \text{observed delay rate at PRT} \\ \omega_{ref} & : \text{reference RF angular frequency} \end{aligned}$$

**27. Residual phase at the earth centered epoch (REARP)** ... REARP is calculated from residual phase at PRT by shifting the epoch by using  $\Delta\dot{\tau}$  as follows,

$$REARP = \text{amod}(\Phi - \Delta T_c \cdot \Delta\dot{\tau} \cdot \omega_{ref}, 2\pi)$$

where

$$\begin{aligned} \Phi & : \text{residual fringe phase at PRT} \\ \Delta T_c & = PRT - ECPRT \\ \Delta\dot{\tau} & = RAT - \Delta\dot{\tau}_{ap} \quad \text{observed residual delay rate} \\ \omega_{ref} & : \text{reference RF angular frequency} \end{aligned}$$

**28. Multi-band correlation amplitude (COHE)** ... COHE is correlation amplitude obtained by a fine search (band-width synthesis) ( $|D(\Delta\tau, \Delta\dot{\tau})|$  is expressed by %).  $D(\Delta\tau, \Delta\dot{\tau})$  is defined as

$$D(\Delta\tau, \Delta\dot{\tau}) = \sum_{n=1}^N \left[ \exp\{-i(\omega_0^n \Delta\tau_m + \Delta\phi_n)\} \cdot \sum_{k=1}^K D_s(n, k) \cdot \exp(-i\omega_0^n \Delta\dot{\tau}_m \cdot T_{pp} \cdot k) \right]$$

where

$$D_s(n, k) = \sum_{j=1}^J S_c^v(j, k, n) \exp\{-i(\omega_j^v \Delta\tau_s + \omega_0^n \Delta\dot{\tau}_s \cdot T_{pp} \cdot k)\}$$

$S_c^v(j, k, n)$  : video cross spectrum by PP, by ch  
 $j < 0$  for LSB,  $j > 0$  for USB  
 $S_c^v = 0$  for  $j = 0$   
 $j$  : video frequency index  
 $J$  : maximum video frequency index  
 $\omega_j^v$  : angular frequency in a video-band  
 $\omega_0^n$  : RF angular frequency for n-ch  
 $T_{pp}$  : PP period  
 $\Delta\phi_n$  : PCAL phase difference for n-ch  
 $\Delta\tau_s, \Delta\tau_m$  : coarse and fine delay residuals  
 $\Delta\dot{\tau}_s, \Delta\dot{\tau}_m$  : coarse and fine delay rate residuals

When delay rate residual  $\Delta\dot{\tau}$  is large, decrease of correlation amplitude due to the phase rotation in a PP is corrected by multiplying a factor given by

$$FACT = \frac{\theta}{\sin \theta} \quad (FACT = 1.0 \text{ when } \theta < 0.01)$$

where

$$\theta = \frac{1}{2} \Delta\dot{\tau} \cdot \omega_{ref} \cdot T_{pp}$$

and it represents the half of the phase rotation in a PP due to delay rate residual.

**29. Fringe amplitude (AAMP)** ... AAMP is calculated by using correlation amplitude incoherently integrated over frequency channels and  $SNR$  as follows.

Let the noise-free fringe amplitude be  $A$ , observed correlation amplitude be  $Z$ , and the variance of noises be  $\sigma^2$ . When  $SNR(= \frac{A}{\sigma}) \gg 0$ ,

$$Z = A \left[ 1 + \frac{\sigma^2}{2A^2} \right]$$

Hence

$$A = \frac{Z}{1 + \frac{\sigma^2}{2A^2}}.$$

$SNR$  obtained by KOMB is that integrated over all channels. Therefore  $SNR$  divided by  $\sqrt{N}$  represents  $SNR$  for each channel. Hence fringe amplitude considering the number of channels is obtained as

$$AAMP = \frac{Z}{1 + \frac{N}{2(SNR)^2}}$$

where

$$Z = \frac{1}{N \cdot K} \sum_{n=1}^N \left| \sum_{k=1}^K D_s(n, k) \right|$$

$N$  : total number of channels

$K$  : total number of PPs per channel

$D_s(n, k)$  : see 28.

$SNR$  : see 30.

(reference: "METHODS OF EXPERIMENTAL PHYSICS I", Vol.12, PART C, pp.244")

**30. Signal to noise ratio (SNR)** ... SNR is calculated as follows,

$$SNR = \frac{2}{\pi} \rho_0 \sqrt{K}$$

where

$K$  : total number of bits (samples) used for processing

$\rho_0$  : corrected correlation amplitude  
=  $COHE$  see 28.

**31. Incoherent segmented fringe amplitude (AICOH)** ... AICOH is fringe amplitude incoherently integrated over channels and time segments. It is calculated as follows,

$$AICOH = \frac{1}{N \cdot K} \sum_{n=1}^N \sum_{l=1}^L \left| \sum_{k=1}^{K_L} D_s(n, k) \right|$$

where

$N$  : total number of channels

$K$  : total number of PPs per channel

$L$  : total number of segments per channel

$K_L$  : the number of PPs per segment

$D_s(n, k)$  : see 28.

$n$  : frequency index

$l$  : segment index

$k$  : PP index in a segment

Segmentation follows a following rule, i.e.,

$$L = \begin{cases} 50 & \text{for } N = 1 \\ \frac{100}{N+2} & \text{for } N > 1 \end{cases}$$

- 32. Probability of false peak detection (PROB)** ... PROB is the probability that errs in detection of the maximum amplitude in coarse and fine searches. It is calculated from the number of search points and  $SNR$ , based on the probability that amplitude of Rayleigh distributed noises exceeds signal correlation amplitude, as follows,

$$PROB = 1.0 - \left( 1.0 - \exp \left\{ -\frac{SNR^2}{2.0} \right\} \right)^M$$

When  $PROB$  computed by this equation is less than 0.01,

$$PROB = M \cdot \exp \left\{ -\frac{SNR^2}{2.0} \right\}$$

where

$M$  : the number of coarse and fine search points

$M = a \cdot b \cdot c$

$a$  : the number of search points for delay domain in a coarse search

$b$  : the number of search points for delay domain in a fine search

$c$  : the number of search points for delay rate domain

$SNR$  : see 30.

- 33. Amplitude and phase by channel (AMPB(2,N))** ... AMPB is coherently integrated correlation amplitude and phase by channel and calculated as follows,

$$\begin{aligned} \text{Amplitude } AMPB(1, n) &= \frac{1}{K_n} \left| \sum_{k=1}^{K_n} D_s(n, k) \right| \\ \text{Phase } AMPB(2, n) &= \arg \left( \sum_{k=1}^{K_n} D_s(n, k) \right) \end{aligned}$$

where

$n$  : frequency channel index

$K_n$  : total number of PPs for n-ch

$k$  : PP number index

$D_s$  : see 28.

$\arg$  : function returning the phase of complex number

- 34. RMS value (QB)** ... QB is the root-mean-square value of the number of PPs over frequency channels. It is calculated as follows,

$$QB = \frac{\sqrt{\frac{1}{N} \sum_{n=1}^N (PP(n) - \overline{NPP})^2}}{\overline{NPP}} \times 100 \quad (\%)$$

where

$PP(n)$  : the number of PPs processed for n-ch

$\overline{NPP}$  : average number of PPs per channel

$\overline{NPP} = (\text{Total number of PPs})/N$

**35. KOMB quality code (KOMBQ or QF)** ... KOMBQ (or QF) is the code to evaluate the processing results objectively. The quality code is either number 0 ~ 9 or a capital letter A~Z. If QF is a capital letter, then it means error is occurred in KOMB processing. If QF is a number, then it means no error in the processing and "9" is the highest quality. How to obtain QF follows the way adopted in the Mark-III VLBI system and it is summarized below.

At first, theoretical and observed variances of fringe phase fluctuation and amplitude fluctuation are computed as follows.

**RMSPT** ... observed rms variation of fringe phases against time (deg)

$$RMSPT = \left[ \frac{\sum_{n=1}^N \sum_{l=1}^L \sin^2 \{ \arg(\sum_{k=1}^{K_L} D_s(n, k)) - \Phi \}}{L \cdot N} \right]^{\frac{1}{2}} \cdot \frac{180}{\pi}$$

where

- $N$  : total number of channels
- $L$  : total number of segments per channel
- $K_L$  : the number of PPs per segment
- $D_s(n, k)$  : see 28.
- $\Phi$  : residual fringe phase (see 19.)

[Note]

$\sin \theta \approx \theta$  is applied for the case  $\theta \ll 1$ . By computing  $\sin$  for residual phase, judgements of ambiguity and quadrant can be omitted.

**RM1** ... theoretical value of RMSPT (deg)

$$RM1 = \frac{1}{SNR} [L \cdot N - 1.0]^{\frac{1}{2}} \cdot \frac{180}{\pi}$$

where see 30. for  $SNR$ .

**RMSAT** ... observed rms variation of correlation amplitudes against time (%)

$$RMSAT = \frac{\left[ \frac{1}{L \cdot N} \sum_{n=1}^N \sum_{l=1}^L \left\{ \frac{1}{K_L} \left| \sum_{k=1}^{K_L} D_s(n, k) \right| - COHE \right\}^2 \right]^{\frac{1}{2}}}{COHE} \times 100 \quad (\%)$$

where see 28. for  $COHE$ .

**RM2** ... theoretical value of RMSAT (%)

$$RM2 = RM1 \cdot \frac{\pi}{180} \cdot 100$$

**RMSPF** ... observed rms variation of fringe phases against channels (deg)

$$RMSPT = \left[ \frac{1}{N} \sum_{n=1}^N \sin^2 \left\{ \arg \left( \sum_{k=1}^{K_L} D_s(n, k) \right) - \Phi \right\} \right]^{\frac{1}{2}} \cdot \frac{180}{\pi}$$

where  $K$  is the number of PPs per channel

**RM3** ... theoretical value of RMSPF (deg)

$$RM3 = \frac{1}{SNR} (N - 1)^{\frac{1}{2}} \cdot \frac{180}{\pi}$$

**RMSAF** ... observed rms variation of correlation amplitudes against frequency channel (%)

$$RMSAF = \frac{\left[ \frac{1}{N} \sum_{n=1}^N \left\{ \frac{1}{K} \left| \sum_{k=1}^K D_s(n, k) \right| - COHE \right\}^2 \right]^{\frac{1}{2}}}{COHE} \times 100 \quad (\%)$$

**RM4** ... theoretical value of RMSAF (%)

$$RM4 = RM3 \cdot \frac{\pi}{180} \cdot 100$$

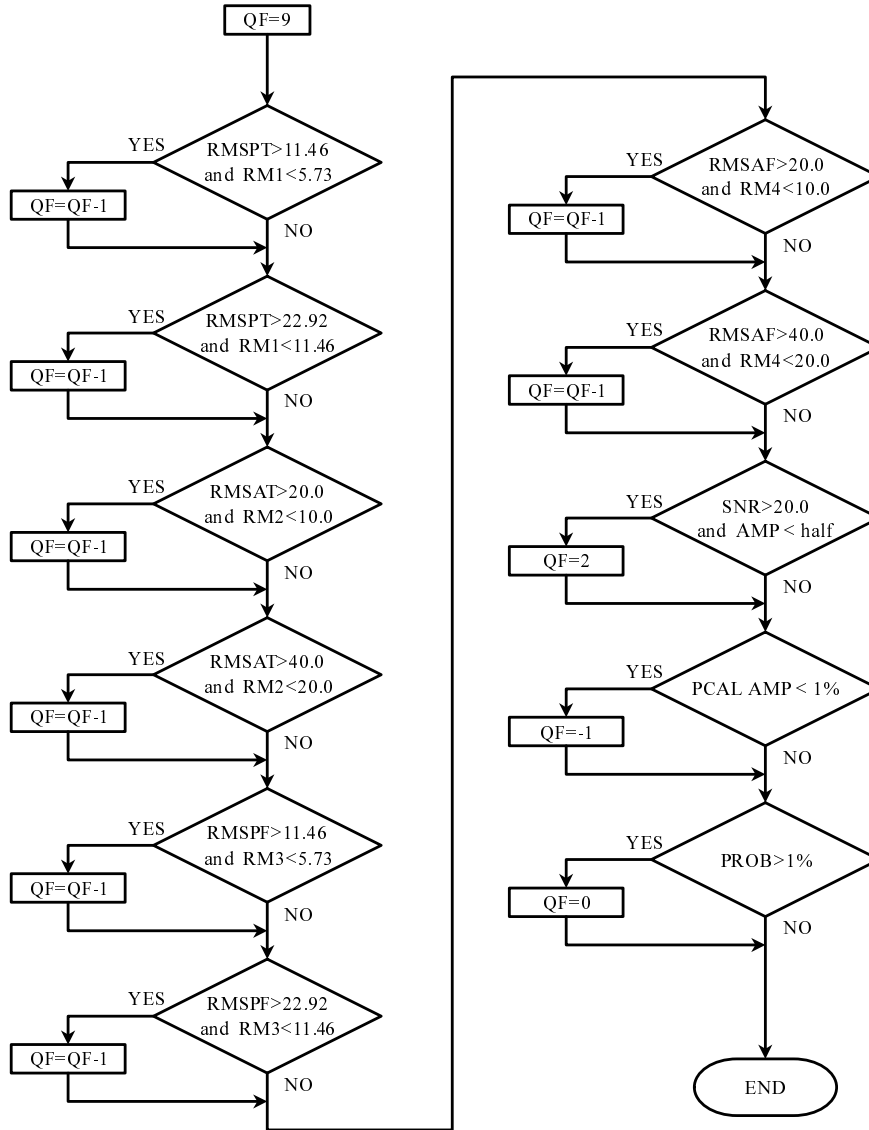


Figure 3: Algorithm to obtain the KOMB quality code “QF”

If KOMB processing is completed without any error, the quality code QF is obtained by following the algorithm showing in Fig.3 by using RMSPT, RMSAT, RMSPF, RMSAF, RM1, RM2, RM3, and RM4. “9” means the highest quality.

[Quality code in the case of error occurrence ]

Quality code for any error occurrence is shown in the table below.

For an example, QF=H denotes the occurrence of ① and ③ errors.

Table 1: KOMB quality code and errors

Errors	Quality code (QF)												
	C	D	E	F	G	H	I	J	M	N	O	R	S
① BOPP is not synchronized among channels	○					○			○			○	
② no PCAL channel existed		○					○			○			○
③ coarse search error occurred			○			○	○				○	○	○
④ fine search error occurred				○									
⑤ PCAL rate search error occurred								○	○	○	○	○	○
⑥ SNR>20 but amplitude is less than the half of other channels					*								

BOPP means the beginning of PP period.

\* no more error at the latest version of KOMB