

Millimeter Interferometry

Proceedings from

IMISS2

“IRAM Millimeter Interferometry Summer School 2”

edited by A.Dutrey^{1,2}

¹ Institut de RadioAstronomie Millimétrique
300 rue de la piscine
F-38406 Saint Martin d'Hères Cedex, FRANCE

² Laboratoire d'Astrophysique de Grenoble
BP53
F-38041 Grenoble Cedex 9, France

In Memoriam

This book is dedicated to the memory of our esteemed colleagues

- Bernard AUBEUF
- Francis GILLET
- Henri GONTARD
- David LAZARO
- Roland PRAYER
- Patrick VIBERT

and of the other 19 persons who died on 1st of July, 1999, in the tragic accident of the cable car giving access to the IRAM interferometer site or on december 15th, 1999, in the crash of the helicopter ensuring transport between the Plateau de Bure and the valley.

Bernard AUBEUF and Patrick VIBERT had been with the IRAM interferometer since the very beginning of its construction. With the help of Henri GONTARD, they had assumed the difficult task of handling the cable car, the general maintenance of the Plateau de Bure buildings, as well as long days of snow clearing to allow the configuration changes in winter. Francis GILLET and Roland PRAYER had been regularly joining the IRAM staff for the summer maintenance, and for the construction of the antennas. David LAZARO was working in the workshop at IRAM headquarters as a precision mechanics.

15 employees of companies working as contractors for IRAM (either on the baseline extension, or on facilities like telephone equipment) also lost their lives in the first accident. 3 engineers working on the telepherique reconstruction and the pilot died in the helicopter crash.

These persons were not astronomers but without their efforts, millimeter astronomy would never have come to the Plateau de Bure site and you would not be reading this book. We wish to dedicate these proceedings to their memory.

Preface

This book contains the updated proceedings from the summer schools held at IRAM in Grenoble from September 14 to September 18, 1998 for IMISS1 and from June 12 to June 16, 2000 for IMISS2. Both schools were attended by more than 50 participants from abroad. Not all lectures have been put in written form: the schools also included a general introduction to millimeter astronomy by Dr. Clemens THUM (IRAM). IMISS2 also contained an introduction on interferometry from the point of view of the quantum mechanics by Dr. Dennis DOWNES (IRAM). A visit to the IRAM interferometer on Plateau de Bure was an essential part of the first school. In the second one, visits to the receiver and correlator laboratories were organized.

The schools would not have occurred without the dedication of Mrs Catherine BERJAUD, who kindly took care of all logistics problems before and during the schools. Dr. Stéphane GUILLOTEAU is also thanked for organizing IMISS1 and doing the edition of the first series of lectures.

During IMISS1, the visit to the interferometer would not have been possible without the contribution of the technical and operator staff of the telescope. Special thanks to the operators Sophie LEONARDON, Michel DAN and André RAMBAUD who also made the films which were presented as an introduction to the Plateau de Bure interferometer at IMISS2. We also acknowledge the receiver and correlator groups who managed the visits to the labs during IMISS2.

We also thank Alain PERRIGOUARD and Roger AHTCHOU for help with the video equipment which gave us a lot of fun during the “real time” sessions.

Finally, Anne DUTREY would like to thank Mrs Cathy BERJAUD for a careful reading of the manuscript, fighting against the last typo errors.

Participants to IMISS1 and IMISS2

This section contains the list and e-mail addresses of participants to IMISS1 and IMISS2 and two photos taken during IMISS2.

Table 1: IMISS1, list of participants

NAME	Email
ANDERSSON Andreas	andreas@astro.su.se
ANTERRIEU Eric	anterrieu@obs-mip.fr
BACMANN Aurore	abacmann@cea.fr
BAUDRY Alain	alain.baudry@observ.u-bordeaux.fr
BERGER Jean-Philippe	berger@obs.ujf-grenoble.fr
BONTEMPS Sylvain	bontemps@astro.su.se
BREMER Michael	bremer@iram.fr
BROOKS Kate	kbrooks@newt.phys.unsw.edu.au
BROWN David	dbrown@mrao.cam.ac.uk
CASTETS Alain	Alain.Castets@obs.ujf-grenoble.fr
CHARMANDARIS Vassilis	Vassilis.Charmandaris@obspm.fr
DOLE Hervé	dole@ias.fr
DUCHENE Gaspard	Gaspard.Duchene@obs.ujf-grenoble.fr
DUTREY Anne	dutrey@iram.fr
DUVERT Gilles	Gilles.Duvert@obs.ujf-grenoble.fr
EISLOFFEL Jochen	jochen@tls-tautenburg.de
GERMAIN Benoit	Benoit.Germain@obspm.fr
GREVE Albert	greve@iram.fr
GUELIN Michel	guelin@iram.fr
GUETH Frédéric	gueth@mpifr-bonn.mpg.de
GUILLOTEAU Stéphane	guillote@iram.fr
HARDER Stephan	Stephan.Harder@obs.ujf-grenoble.fr
HERPIN Fabrice	herpin@observ.u-bordeau.fr
ISAAC Kate	isaak@astro.umd.edu
KLEIN Randolph	rklein@otto.astro.uni-jena.de
KRAUSE Oliver	krause@mpia-hd.mpg.de
LAZAREFF Bernard	lazareff@iram.fr
LEFLOCH Bertrand	lefloch@astro.iem.csic.es
LOINARD Laurent	Laurent.Loinard@obs.ujf-grenoble.fr
LUCAS Robert	lucas@iram.fr
MALBET Fabien	Fabien.Malbet@obs.ujf-grenoble.fr
MAOLI Roberto	maoli@mesioa.obspm.fr
MINIER Vincent	vincent@oso.chalmers.se
MONIN Jean-Louis	monin@obs.ujf-grenoble.fr
MORENO Rafael	moreno@iram.fr
MOTTE Frédérique	Fmotte@cea.fr
NAVARRINI Alessandro	navarrin@iram.fr
NERI Roberto	neri@iram.fr
NICCOLINI Gilles	nicolin@obs-nice.fr
NIETEN Christoph	chnieten@mpifr-bonn.mpg.de
PANIS Jean-François	panis@biaa.sinica.edu.tw
PISANU Tonino	tpisanu@ira.bo.cnr.it
RAVERA Laurent	Laurent.Ravera@cesr.fr
ROBERT Didier	robert@iram.fr

Table 2: IMISS1, list of participants continued

NAME	Email
SANCHEZ CONTRERAS Carmen	sanchez@oan.es
SCHNEIDER Nicola	schneider@ph1.uni-koeln.de
TARCHI Andrea	atarchi@astro.uni-bonn.de
THUM Clemens	thum@iram.fr
TRIGILIO Corrado	trigilio@ira.noto.cnr.it
UMANA Grazia	umana@ira.noto.cnr.it
WIESEMEYER Helmut	wiesemey@iram.fr
WILD Wolfgang	wild@iram.es

Table 3: IMISS2, list of participants

NAME	Email
ARCE Hector	harce@cfa.harvard.edu
AUGEREAU Jean-Charles	Jean-Charles.Augereau@obs.ujf-grenoble.fr
BACMANN Aurore	bacmann@astro.uni-jena.de
BELLOCHE Arnaud	belloche@discovery.saclay.cea.fr
BELTRAN Maria-Teresa	mbeltran@cfa.harvard.edu
BERGER Jean-Philippe	berger@enserg.fr
BIOLLUZ Gilles	gbiolluz@yahoo.com
BOONE Frederic	Frederic.Boone@obspm.fr
BREMER Michael	bremer@iram.fr
BRETHERTON Derek	deb@astro.livjm.ac.uk
CASTRO-CARRIZO Arancha	Carrizo@oan.es
CECARELLI Cecilia	Cecilia.Cecarelli@obs.ujf-grenoble.fr
COLOM Pierre	colom@obspm.fr
COMITO Claudia	ccomito@mpifr-bonn.mpg.de
CONTINI Thierry	tcontini@eso.org
DAN Michel	dan@iram.fr
DANNERBAUER Helmut	dannerb@mpe.mpg.de
DARTOIS Emmanuel	dartois@iram.fr
DELGADO Guillermo	gdelgado@eso.org
DE VRIES Christopher	devries@astro.umass.edu
DOWNES Dennis	downes@iram.fr
DUTREY Anne	dutrey@iram.fr

Table 4: IMISS2, list of participants continued

NAME	Email
ELS Sebastian	sels@eso.org
FOSSE David	fosse@isis.iem.csic.es
GALLEG CALVENTE Teresa	tgallego@iram.es
GREVE Albert	greve@iram.fr
GROSSO Nicolas	ngrosso@xray.mpe.mpg.de
GUETH Frédéric	gueth@iram.fr
GUILLOTEAU Stéphane	guillote@iram.fr
HAFOK Heiko	hafok@ph1.uni-koeln.de
HAGUENAUER Pierre	Pierre.Haguenauer@obs.ujf-grenoble.fr
HAIKALA Lauri	lhaikala@sc.eso.org
HENRY Florence	Florence.Henry@obspm.fr
HILY-BLANT Pierre	hilyblan@iram.es
KERVELLA Pierre	pkervell@eso.org
LAZAREFF Bernard	lazareff@iram.fr
LE FLOCH'H Emeric	elefloch@eso.org
LEONARDON Sophie	Leonardo@iram.fr
LOINARD Laurent	loinard@iram.fr
LUCAS Robert	lucas@iram.fr
MALBET Fabien	Fabien.Malbet@obs.ujf-grenoble.fr
MAO Ruiqing	rqmao@mpifr-bonn.mpg.de
MAUERSBERGER Rainer	mauers@iram.es
MEGE Pierre	Pierre.Mege@obs.ujf-grenoble.fr
MELCHIOR Anne-Laure	A.L.Melchior@obspm.fr
MORENO Raphael	moreno@iram.fr
MUELLER Sebastien	muller@iram.fr
NAKANISHI kouichiro	nakanisi@nro.nao.ac.jp
NERI Roberto	neri@iram.fr
NICCOLINI Gilles	nicolin@obs-nice.fr
NUERNBERGER Dieter	nurnberger@iram.fr
OTAROLA Angel	aotarola@eso.org
PARDO CARRION Juan Ramon	pardo@isis.iem.csic.es
PETY Jérôme	pety@Ira.ens.fr
PRIEUR Jean-Louis	jean-louis.prieur@ast.obs-mip.fr
RAMBAUD André	rambaud@iram.fr
SCHREYER Katharina	martin@astro.uni-jena.de
SEGRANSAN Damien	Damien.Segransan@obs.ujf-grenoble.fr
TEYSSIER David	teyssier@Ira.ens.fr
THI Wing-Fai	thi@strw.leidenuniv.nl
THOMAS Bertrand	thomas@iram.es
THUM Clemens	thum@iram.fr
VALLEJO Olivier	vallejo@observ.u-bordeaux.fr
VASTEL Charlotte	Charlotte.Vastel@cesr.fr
WIESEMAYER Helmut	wiesemey@iram.fr
WILGENBUS David	david.wilgenbus@obspm.fr
ZUCCONI Antonio	zucconi@arcetri.astro.it



Figure 1: Participants to IMISS2



Figure 2: Participants to IMISS2

Contents

In Memoriam	iii
Preface	v
Participants to IMISS1 and IMISS2	vii
1 Radio Antennas	1
1.1 Introduction	1
1.2 Basic Principles	2
1.3 The perfect Single–Dish antenna	3
1.4 The real Single–Dish Antenna	7
1.4.1 Systematic Deformations: Defocus, Coma, Astigmatism	7
1.4.2 Random Errors	10
1.5 Radiometric Relations	13
2 Millimetre Interferometers	15
2.1 Basic principle	15
2.2 The Heterodyne Interferometer	17
2.2.1 Source Size Effects	17
2.2.2 Finite Bandwidth	19
2.3 Delay Tracking and Frequency Conversion	20
2.4 Fringe Stopping and Complex Correlator	21
2.5 Fourier Transform and Related Approximations	21
2.6 Array Geometry & Baseline Measurements	23
3 Millimetre Very Long Baseline Interferometry	25
3.1 Introduction	25
3.2 mm–VLBI Arrays	26
3.2.1 The CMVA Array	26
3.2.2 The VLBA Array	29
3.3 Available Resolution	29
3.4 Polarization Observations	31
3.5 The Feasibility of mm–VLBI: Signal–to–Noise Ratio and Detections	31
3.6 From observations to correlations, step by step	32
3.6.1 Observing Techniques	32
3.6.2 Data Recording	36
3.6.3 Correlation Time	36
3.6.4 Phase Correction	36
3.6.5 Correlation	36
3.7 The observable sources with mm–VLBI	38
3.7.1 Which Kind of sources can we observe	38
3.7.2 The field of view	38
3.7.3 An example: mm–VLBI Observations of QSO 3C 273	40

4 Introduction to Optical/Near-Infrared Interferometry	43
4.1 Introduction	43
4.1.1 Brief history of optical interferometry	43
4.1.2 Current and future optical interferometers	44
4.2 Optical versus millimeter radio interferometry	45
4.2.1 Common issues	45
4.2.2 Main differences	45
4.3 Description of optical interferometers	46
4.3.1 Functional description	46
4.3.2 Specific applications	49
4.4 Formation of the interferometric fringes	51
4.4.1 Beam combination	51
4.4.2 Fringe coding and detection	53
4.5 Main challenges in interferometry	53
4.5.1 Atmosphere turbulence	54
4.5.2 Other atmosphere systematics	54
4.5.3 Fighting the atmosphere: complexity and accuracy	55
4.5.4 Noise sources - Sensitivity	55
4.6 Conclusion	56
5 Receivers : an overview for non-specialists	63
5.1 Introduction	63
5.2 Coupling optics	63
5.3 Why we need heterodyne receivers	66
5.4 Local oscillator system	67
5.5 Local oscillator injection	67
5.6 Photon-assisted tunneling	67
5.7 Mixer	69
5.8 Cryostat	70
5.9 Actual receivers	70
6 Cross Correlators	73
6.1 Introduction	73
6.2 Basic Theory	74
6.3 The Correlator in Practice	77
6.3.1 Digitization of the input signal and clipping correction	78
6.3.2 Time lag windows and spectral resolution	82
6.3.3 Main limitations	83
6.4 The correlator on Plateau de Bure	87
6.4.1 The third-generation correlator	87
6.5 Appendix	88
6.5.1 Summary of definitions	88
6.5.2 Clipping correction for 4-level quantization	89
7 LO System and Signal Transport	91
7.1 An Heterodyne Interferometer	91
7.1.1 The simple interferometer	91
7.1.2 The heterodyne interferometer	91
7.1.3 Frequency conversion	92
7.1.4 Signal phase	92
7.2 Delay lines requirements	94
7.2.1 Single sideband processing in a finite bandwidth	94
7.2.2 Double sideband system	95
7.3 sideband separation	95

7.3.1	Fringe rate method	95
7.3.2	Phase switching method	95
7.4	The PdB Signal and LO transport system	96
7.4.1	Signal path	96
7.4.2	LO generation	98
7.4.3	Further signal processing	98
7.4.4	Phase stability requirements	98
7.4.5	Cable electrical length control	99
7.5	Next generation instruments	99
8	The Plateau de Bure Interferometer	101
8.1	History	101
8.2	Description	101
8.3	Array operation	103
8.3.1	Array calibration	103
8.3.2	Array observations	106
8.4	Proposal submission and contact people	108
9	Bandpass and Phase Calibration	111
9.1	Definitions and formalism	111
9.1.1	Baseline based vs antenna based gains	112
9.1.2	Gain corrections	113
9.2	Bandpass calibration	113
9.2.1	Bandpass measurement	113
9.2.2	IF passband calibration	113
9.2.3	RF bandpass calibration	114
9.2.4	Sideband calibration	115
9.3	Phase calibration	115
9.3.1	Phase referencing by a nearby point source	116
9.3.2	Phase referencing by a point source in the primary beam	117
9.3.3	Phase referencing using another band or another frequency	117
10	Atmospheric Absorption	119
10.1	The physical and chemical structure of the Atmosphere	119
10.1.1	Constituents of the atmosphere	119
10.1.2	Thermodynamics of the air	120
10.1.3	Hydrostatic equilibrium	121
10.1.4	Water	122
10.2	Atmospheric radiative transfer in the mm/submm	122
10.2.1	Introduction	122
10.2.2	Unpolarized radiative transfer equation	122
10.2.3	Spectroscopic parameters	123
10.2.4	Line shapes	125
10.2.5	Non-resonant absorption	126
10.2.6	Radiative transfer through atmospheric hydrometeors	127
10.3	Fourier Transform Spectroscopy for site testing	128
10.3.1	FTS measurements at Mauna Kea	128
10.3.2	FTS measurements at Atacama (future ALMA site)	130
10.4	Atmospheric absorption evaluation	131
10.4.1	Correction for atmospheric absorption, T_A^*	131
10.5	Phase fluctuation evaluation	134
10.5.1	Cause of Phase Fluctuations	134
10.5.2	Simulations of phase fluctuations	134
10.5.3	Phase Correction Methods	134

10.5.4 Example of phase correction	135
11 Atmospheric Fluctuations	139
11.1 Introduction	139
11.2 Hydrodynamical basics of turbulent motion	141
11.3 Statistical properties of turbulence	143
11.4 Remote sounding techniques	145
11.5 Current phase correction at IRAM	146
11.6 Phase correction during off-line data reduction	149
11.7 Frequently asked questions	150
12 Amplitude and Flux Calibration	153
12.1 Definition and Formalism	153
12.2 Single-dish Calibration of the Amplitude	154
12.2.1 Low opacity approximation and implication for T_{cal}	155
12.2.2 Absolute errors on T_{cal} due to instrumental parameters	156
12.2.3 Relative errors or errors on T_{cal}^L/T_{cal}^U	156
12.2.4 Estimate of the thermal noise	159
12.3 Flux Calibration (visitor's nightmare)	159
12.3.1 Introduction	159
12.3.2 Calibration procedure at Bure	160
12.3.3 Determining the absolute flux scale on a project	161
12.3.4 Possible biases and remedies	162
12.3.5 The program FLUX	164
12.4 Interferometric Calibration of the Amplitude	164
12.4.1 Correction for the antenna gain $\Gamma_i(t)$	164
12.4.2 Estimate of the atmospheric decorrelation factor f	165
12.4.3 Fitting Splines: the last step	168
12.4.4 A few final checks	168
13 Calibration of data in Practice	171
13.1 Introduction	171
13.1.1 Contents of the account	171
13.1.2 Before starting the data reduction	172
13.1.3 Activating the CLIC environment	172
13.2 The "First Look" procedure	172
13.3 The "Standard Calibration (2-receivers)" procedure	173
13.3.1 Inputs	174
13.3.2 Actions or Outputs	174
13.3.3 Results of the calibration	175
14 UV Plane Analysis	177
14.1 <i>uv</i> tables	177
14.1.1 <i>uv</i> table contents	177
14.1.2 How to create a <i>uv</i> Table	178
14.2 <i>uv</i> data plots	179
14.3 Data editing	180
14.4 Position shift	181
14.5 Averaging	181
14.5.1 Data compression	181
14.5.2 Circular averaging	182
14.6 Model fitting	182
14.6.1 Position measurement	183
14.7 Continuum source subtraction	183
14.8 Self calibration by a point source	183

15 The Imaging Principles	187
15.1 Fourier Transform	188
15.1.1 Direct Fourier Transform	188
15.1.2 Fast Fourier Transform	188
15.1.3 Gridding Process	188
15.2 Sampling & Aliasing	189
15.3 Convolution and Aliasing	189
15.4 Error Analysis	191
15.5 Weighing and Tapering	191
15.6 The GILDAS implementation	193
15.7 Deconvolution	193
15.7.1 The CLEAN method	194
15.7.2 Interpretation of CLEAN	195
15.7.3 The CLEAN variants	195
15.7.4 The GILDAS implementation	196
16 Advanced Imaging Methods: WIPE	197
16.1 Introduction	197
16.2 Object space	198
16.3 Experimental data space	199
16.4 Image reconstruction process	200
16.4.1 Synthesized aperture	200
16.4.2 Synthetic beam	201
16.4.3 Regularization frequency list	201
16.4.4 Data space	202
16.4.5 Object representation space	202
16.4.6 Objective functional	202
16.4.7 Uniqueness and robustness	203
16.5 Implementation of WIPE at IRAM	206
17 Mosaicing	209
17.1 Introduction	209
17.2 Image formation in a mosaic	210
17.3 Mosaicing in practice	212
17.4 A CLEAN-based algorithm for mosaic deconvolution	214
17.5 Artifacts and instrumental effects	217
17.6 Concluding remarks	219
18 Imaging in Practice	221
18.1 Visualisation	221
18.2 Photometry	222
18.2.1 From Flux density to Brightness temperature	222
18.2.2 Accuracy of Flux density estimates	222
18.3 Short Spacings	224
18.3.1 UV_SINGLE	224
18.4 Dirty Tricks	225
18.4.1 MOMENTS	225
18.4.2 Continuum Subtraction	226
19 Low Signal-to-noise Analysis	227
19.1 Continuum Source	227
19.1.1 Flux measurement	227
19.1.2 Other parameters	228
19.2 Spectral Line Sources	230

20 Basic Principles of Radio Astrometry	233
20.1 Introduction and Basic Formalism	233
20.2 The Phase Equation	234
20.3 Determination of Source Coordinates and Errors	235
20.4 Accurate Position Measurements with the IRAM Interferometer	236
20.4.1 Absolute positions	237
20.4.2 Relative Positions and Self-calibration Techniques	238
20.5 Sources of Position Uncertainty	239
20.5.1 Known Limitations	240
20.5.2 Practical Details	240
21 Mm versus Optical Interferometry: a qualitative comparison	243
21.1 The basic equation of interferometry	243
21.1.1 Additive interferometry	244
21.1.2 Multiplicative interferometry	244
21.2 Getting the fringes	244
21.3 Atmospheric behaviour and noise properties	245