Electronic Imaging in Astronomy

Detectors and Instrumentation (Second Edition)

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Springer

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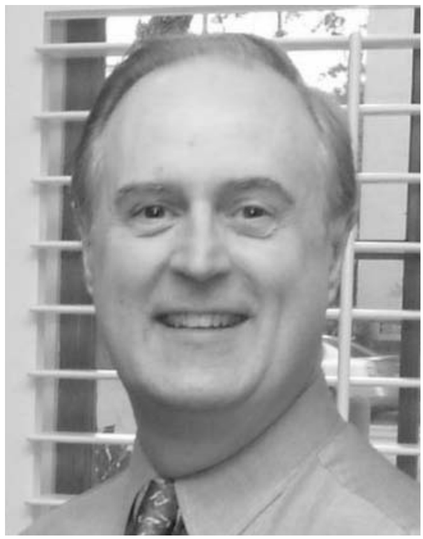
About the author

Professor Ian S. McLean received his PhD in Astronomy from Glasgow University (U.K.) in 1974. While a member of staff at the Royal Observatory Edinburgh from 1979 to 1989 he developed the first CCD-based imaging spectro-polarimeter and the first facility-class infrared camera. He has been a member of the faculty of the Department of Physics and Astronomy at the University of California, Los Angeles and Director of the Infrared Laboratory since 1989. McLean is one of the world's leading authorities on the application of electronic imaging systems to advanced astronomical instrumentation. He served on the Science Steering Committee for the W. M. Keck Observatory for ten years and he has been team leader or co-investigator on several pioneering Keck instruments.



Preface

Throughout history astronomy has relied heavily on advances in technology. In some cases, astronomers have been the driving force behind those developments. Today's telescopes and observatories, whether on the ground or in space, are "high-tech" places where state-of-the-art electronic equipment is used to collect and analyze all forms of light. Driven by new technology, discoveries and revelations about the Universe have been coming at an incredible pace in recent years. Yet the demand for more sensitivity and better equipment is greater now than ever before. Modern astronomy is therefore as exciting and challenging for the professional engineer and applied physicist as it is for the astronomer. Moreover, would-be astronomers must reckon on acquiring a wide range of skills, or on working as a member of a multi-disciplinary team.

The first edition of *Electronic Imaging in Astronomy: Detectors and Instrumentation*, published in 1997, grew out of a precursor called *Electronic and Computer-Aided Astronomy: From Eyes to Electronic Sensors* which was stimulated by the desire to explain to others just how much applied physics and engineering goes into the seemingly "pure" science of astronomy. That earlier book, published in 1989, was also inspired by the remarkable impact which one small "silicon microchip", the CCD, had on astronomical imaging methods. For the 1997 book I added material on general principles and techniques, while maintaining a valuable historical perspective, and broadened the scope to include the remarkable growth of astronomical imaging across the entire electromagnetic spectrum, including my own area of infrared arrays. Since then, the rapid pace of technology and discovery has wrought many other fundamental changes in observational astronomy which have dated that account. For example, we have witnessed the success of numerous astronomical space missions, realized the importance of highly automated survey telescopes, and entered the era of very large telescopes. The CCD remains as ubiquitous as ever, but imaging is now possible at almost any wavelength from gamma rays to radio waves. Too often, the sophisticated and elegant instruments available at observatories are viewed by students as a "black box". I would like my students to know what is inside the box, and how much effort it took to get it there. I hope this new edition will encourage more college courses on detectors and instrumentation for astronomy, but equally important, I hope it will encourage an even greater appreciation of the remarkable link between astronomy and technology.

This new edition builds on the successful format of the previous book. The text has been written on several levels in the hope that a wide range of people will be able to find something in it for them. In addition, the flow of the book has been arranged to be more useful as a college text on astronomical instruments and techniques. By using "electronic imaging" as a unifying theme, the aim is to provide a simplified, broad-based introduction to astronomical detectors and instrumentation that would be suitable for advanced undergraduate students and new graduate students who need a background in observational methods. Breadth rather than depth is more useful for students who have yet to choose their final career path. Inevitably there will be gaps in the coverage given the broad scope, but it is hoped that enough leads to other sources have been provided to help the reader follow any path of interest. By retaining some historical content and collecting diverse information in one volume, it is hoped that the book also serves as a useful reference for established professionals and anyone interested in this most important aspect of astronomy. Chapter 1 identifies the "observables" and provides a general introduction to electronic imaging. Chapter 2 treats the Earth's atmosphere and describes how Adaptive Optics is helping ground-based astronomy to compete with space. Chapter 3 contains an introduction to astronomical telescopes and the technologies behind the new very large telescopes. Chapter 4 illustrates the discovery power of astronomical detectors and instruments to explain what cameras and spectrometers do. Chapter 5 gives basic descriptions of the fundamental instruments of "optical" astronomy (i.e., the techniques that generally apply from the ultraviolet to the infrared). Detector classification is also explained, and semiconductors are introduced. Chapter 6 expands the discussion of instrumentation with an introductory tutorial for those interested in designing and building instruments. Chapters 7 and 8, respectively, give the basic principles of the CCD and then details on practical operation. Chapter 9 deals with a wide range of important calibration issues common to most electronic imaging devices and explains concepts such as flat-fielding and signal-to-noise ratios. An introduction to the techniques of image processing is given in Chapter 10. The remaining chapters expand the discussion to all the other wavebands, using the story of the CCD to link many of them together. Chapter 11 treats the revolutionary "infrared array" detector. Electronic imaging from UV to gamma rays is treated in Chapter 12. Chapter 13 explores electronic imaging from the sub-millimeter to the meter bands of radio astronomy. Finally, in Chapter 14, we look towards the future and speculate on the prospects for the development of new detectors and telescopes.

The approach is largely practical, with an emphasis on how things work. Historical perspectives are included because I have found that they are motivational, especially the role that modern astronomers and technologists have played in the development and exploitation of electronic imaging. Derivations of well-known material are not included, and mathematical expositions are at the undergraduate level. Many college observatories have telescopes equipped with CCD cameras. This book can be used for a one-semester introductory course on modern astronomical detectors and instruments, and as a supplement for a practical or laboratory class. By supplementing this book with some more advanced material on optics and detector physics, this text also provides the core of an advanced course on astronomical instrumentation for new graduate (PhD) students. This book is also intended to be a useful reference for professionals in the scientific instrumentation field.

I would like to take this opportunity to thank all who helped and encouraged this work. I am particularly indebted to the Series Editor John Mason for his advice and to my publisher Clive Horwood of Praxis for his patience and long-time support. Many, many people kindly supplied me with information, reference materials, and photographs. In addition to all who helped with the earlier books, I especially wish to thank this time, Sean Adkins, Rachel Akeson, Taft Armandroff, Eric Becklin, Jim Beletic, Mike Bolte, Mark Casali, Eric Craine, George Djorgovski, Alex Filippenko, Bob Fischer, Neil Gehrels, James Graham, Don Hall, Martin Hardcastle, Wayne Holland, Mark Hunten, Derek Ives, Jim Janesick, Paul Jorden, James Larkin, David Leisawitz, Keith Matthews, Craig McCreight, Craig Mackay, Gerry Neugebauer, Rene Ong, Rene Racine, Chuck Steidel, Richard Stover, Jean Turner, Tony Tyson, John Vallerga, Greg Wirth, Peter Wizinowich, Erick Young, and Jonas Zmuidzinas.

It is a particular pleasure to acknowledge the many fine engineers and technologists that I have been privileged to work with over the years including my current team at the UCLA Infrared Lab in Los Angeles, as well as my former colleagues at the Royal Observatory Edinburgh (ROE), most especially the late Donald Pettie. During the writing of this second edition I was lucky to spend a sabbatical leave back in Edinburgh at ROE, now called the Astronomy Technology Centre (ATC). I am grateful to the Scottish Universities Physics Alliance (SUPA) for their support, and I want to thank Colin Cunningham and the entire ATC staff for their hospitality. Thanks too to my thesis adviser David Clarke (Glasgow University) who set me on the road to instrumentation. As a dedicated teacher, I also want to thank all of my students and postdocs over the years from whom I have learned so much. Finally, I am most appreciative of the unswerving support of my wife Jan and my family. I look forward to hearing from readers and teachers.

Ian McLean
Edinburgh and Los Angeles
March 2008

To my father,
for showing me the stars
and
to my family,
for being my stars

Figures

Tables

Abbreviations and acronyms

2dF	Two degree Field
2dFGRS	Two degree Field Galaxy Redshift Survey
2MASS	Two Micron All Sky Survey
6dF	Six degree Field
A/D	Analog to Digital
AAT	Anglo-Australian Telescope
ADC	Analog to Digital Converter; Atmospheric Dispersion Compensator; Atmospheric Dispersion Corrector
ADS	Astrophysics Data System
ADU	Analog-to-Digital Unit
AGN	Active Galactic Nuclei
AIPS	Astronomical Image Processing System
ALMA	Atacama Large Millimeter Array
ANSI	American National Standards Institute
AO	Adaptive Optics
AR	Anti-Reflection
ASCII	American Standard Code for Information Interchange
ASIC	Application Specific Integrated Circuit
ATRAN	Atmospheric TRANsmission code
BCCD	Buried Channel CCD
BIB	Blocked Impurity Band
BN	Becklin–Neugebauer
CADC	Canadian Astronomy Data Center
Caltech	California Institute of Technology
CARA	California Association for Research in Astronomy
CCD	Charge-Coupled Device
CCPS	California and Carnegie Planet Search
CCR	Closed Cycle Refrigerator

CDS	Correlated Double Sampling
CFHT	Canada–France–Hawaii Telescope
CGRO	Compton Gamma Ray Observatory
CHARA	Center for High Angular Resolution Astronomy
CID	Charge Injection Device
CMB	Cosmic Microwave Background
CMOS	Complementary Metal Oxide Semiconductor
COBE	COsmic Background Explorer
COTS	Commercial Off The Shelf
CRT	Cathode Ray Tube
CSO	Caltech Sub-millimeter Observatory
CTE	Charge Transfer Efficiency
CTIO	Cerro Tololo Inter-American Observatory
CW	Continuous Wave
CXO, CXRO	Chandra X-ray Observatory
CZT	Cadmium Zinc Telluride
D/H	Deuterium to Hydrogen
DCG	DiChromated Gelatin (layer)
DENIS	European DEep Near-Infrared Survey
DM	Deformable Mirror
DMA	Direct Memory Access
DN	Data Number
DQE	Detective Quantum Efficiency
DSB	Double SideBand
DSP	Digital Signal Processor
DSS	Digitized Sky Survey
E-ELT	European Extremely Large Telescope
EEV	English Electric Valve, now *e2v technologies*
EFL	Effective Focal Length
ELT	Extremely Large Telescope
EMCCD	Electron Multiplied CCD
EPROM	Erasable PROM
ESA	European Space Agency
ESO	European Southern Observatory
EUVE	Extreme UltraViolet Explorer
FCC	Federal Communications Commissions
FEA	Finite Element Analysis
FET	Field Effect Transistor
FITS	Flexible Image Transport System
FOV	Field Of View
FP	Fabry–Perot
FPA	Focal Plane Array
FPGA	Field Programmable Gate Array
FTS	Fourier Transform Spectrometer
FUSE	Far Ultraviolet Spectroscopic Explorer

FWHM	Full Width at Half Maximum
GALEX	GALaxy Evolution EXplorer
GBT	Green Bank Telescope
GLAST	Gamma-ray Large Area Space Telescope
GMT	Giant Magellan Telescope
GNAT	Global Network of Automated Telescopes
GPS	Global Positioning System
GRB	Gamma Ray Burster; Gamma Ray Burst
GTC	Gran Telescopio Canarias
GUI	Graphical User Interface
HD	Henry Draper
HDF	Hubble Deep Field
HESS	High Energy Stereoscopic System
HET	Hobby–Eberly Telescope
HR	Hertzsprung–Russell
HST	Hubble Space Telescope
IBC	Impurity Band Conduction
ICRF	International Celestial Reference Frame
IDL	Interactive Data Language
IEC	International Electrotechnical Commission
IF	Intermediate Frequency
IFU	Integral Field Unit
IPAC	Infrared Processing and Analysis Center
IRAF	Image Reduction and Analysis Facility
IRAS	InfraRed Astronomical Satellite
ISO	Infrared Space Observatory
IUE	International Ultraviolet Explorer
IVOA	International Virtual Observatory Alliance
JAXA	Japan Aerospace eXploration Agency
JCMT	James Clerk Maxwell Telescope
JFET	Junction Field Effect Transistor
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KAO	Kuiper Airborne Observatory
L3CCD	Low Light Level CCD
LED	Light Emitting Diode
LLNL	Lawrence Livermore National Labs
LO	Local Oscillator
LPE	Liquid Phase Epitaxy
LSB	Least Significant Bit
LSST	Large Synoptic Survey Telescope
LST	Local Sidereal Time
LUT	Look Up table
MAMA	Multi-Anode Microchannel Array
mas	milli-arcsecond

MBE	Molecular Beam Epitaxy
MCP	MicroChannel Plate
MCT	Mercury Cadmium Telluride (HgCdTe)
MEMS	Micro-Electro-Mechanical Systems
MKID	Microwave Kinetic Inductance Detector
MKS	Meter, Kilogram, Second (metric units)
MOS	Metal Oxide Semiconductor
MOVPE	Metal Organic Vapor Phase Epitaxy
MPPCCD	Multi-Pinned Phase CCD
MTF	Modulation Transfer Function
NASA	National Aeronautics and Space Administration
NEFD	Noise Equivalent Flux Density
NEP	Noise Equivalent Power
NIST	National Institute of Standards and Technology
NOAO	National Optical Astronomy Observatories
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
OAP	Off Axis parabola
OFHC	Oxygen Free High Conductivity
op-amp	operational amplifier
OPD	Optical Path Difference
OTCCD	Orthogonal Transfer CCD
P-V	Peak-to-Valley
Pan-STARRS	Panoramic Survey Telescope And Rapid Response System
PCB	Printed Circuit Board
PCI	Peripheral Component Interconnect
PI	Principal Investigator
PMT	PhotoMultiplier Tube
POSS	Palomar Observatory Sky Survey
PROM	Programmable Read Only Memory
PSF	Point Spread Function
QE	Quantum Efficiency
rms	root mean square
ROE	Royal Observatory Edinburgh
ROIC	ReadOut Integrated Circuit
RVS	Raytheon Vision Systems
SALT	South African Large Telescope
SDSS	Sloan Digital Sky Survey
SIS	Superconductor–Insulator–Superconductor
SKA	Square Kilometer Array
SNR, S/N	Signal to Noise Ratio
SOFIA	Stratospheric Observatory For Infrared Astronomy
SQUID	Superconducting QUantum Interference Device
SR	Strehl Ratio
STScI	Space Telescope Science Institute

TDI	Time Delay and Integration; Time Delay Integration
TES	Transition Edge Sensor
TMA	Three Mirror Anastigmat
TMT	Thirty Meter Telescope
TTL	Transistor Transistor Logic
UBV	Ultraviolet, Blue, Visual (yellow)
UCO	University of California Observatories
UKIRT	U.K. InfraRed Telescope
UV/O/IR	UltraViolet, Optical, InfraRed
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLA	Very Large Array
VLBI	Very Long Baseline Interferometry
VLT	Very Large Telescope
VPH	Volume Phase Holographic
WF/PC, WFPC	Wide Field/Planetary Camera
WFE	WaveFront Error
WIYN	Wisconsin–Indiana–Yale and NOAO
WMAP	Wilkinson Microwave Anisotropy Probe
WMKO	W.M. Keck Observatory

Introduction

One summer when I was a small boy, my father told me the names of the brightest stars and pointed out the patterns of the major constellations. His knowledge of the night sky came from navigation experience as a sailing master on large cargo ships. I was fascinated, and wanted to go out every night to observe the stars. All astronomers talk about "going observing", but what does this mean? If you are an amateur enthusiast then it may mean going no farther than your backyard or your local astronomy club. For professional astronomers, however, the phrase means much more. Implicit is the fact that to understand the Universe we must observe it, and to do so we will need more than our human eyes. We will need all that modern electronic technology can offer. Today, the largest ground-based telescopes are located at relatively remote, pristine sites, high above sea level where the air is thin and the skies are astonishingly clear. So "going observing" can also mean going far away from home.

Access by professional astronomers to national ground-based observatories, as well as most university or privately owned facilities, is on a highly competitive basis. To obtain an allocation of "observing time" an astronomer must submit in writing a well-argued scientific case for his or her observational experiment. Deadlines are set typically twice or three times per year. Selection is done by peer review (i.e., by a committee formed from the body of scientists who actually use the facility). Unfortunately, all of the major telescopes are heavily oversubscribed, so disappointment is a fact of life. To maximize the progress of scientific experiments at each facility, and to make the optimum use of weather conditions, the astronomical community world-wide has expended considerable effort on technology. This means highly automated observatories with much reliance on well-engineered instrumentation and computers, and it also implies new cost-effective solutions for the design and management of telescopes and equipment. Observing time on large telescopes is therefore difficult to obtain and is very valuable; it is important that no time be wasted. Also, modern observatories are quite complex, and so guest astronomers who may visit only twice per year cannot be expected to learn the myriad of operational details. To solve this problem, all large observatories provide one or more highly trained personnel to support the visitor. Usually a night assistant/ telescope operator will be provided; he or she will be responsible for control of the telescope and dome, ensuring efficient operation and keeping an observatory logbook. Other staff will be responsible for the preparation of observing equipment. The night assistant has the final word regarding safety matters, such as closing the telescope dome if the wind speed becomes too high. Sometimes a support scientist, who is a professional research astronomer on the observatory staff familiar with the instrumentation, will be available to assist first-time or irregular users of the telescope.

A guest observer (or GO) planning to use a modern, computer-controlled electronic imaging camera or spectrograph at one of these major facilities might encounter the following pattern of work. Visiting astronomers will probably arrive by air a few days before their allocated time to ensure that they are not travel-weary and to discuss their plans with observatory staff. They may have traveled from North America or Europe to Hawaii, or to Chile or Australia, or any of several other destinations. By mid-afternoon before the first night on the telescope, the observatory staff will be in the telescope dome making sure that the telescope and the instrument are functioning correctly. The visiting astronomer(s), often including graduate students receiving training in observational methods or seeking data for a thesis topic, may well elect to be present for these checks, and may wish to practice using the instrument. This may mean becoming familiar with a control panel, or with the operation of a computer console on which the observational modes can be displayed and changed by typing at a keyboard. To feel confident that they understand the operation of the instrument, the visiting astronomers will carry out some tests of their own such as a "noise check" on the detector, or a calibration image or spectrum. With everything ready for the evening, they return to the observatory residential lodge where a meal might be prepared for them or to make their own. This is usually a great chance to meet people from all over the world, and the dinner conversation is often buzzing with astronomical jargon! Just prior to sunset the "observers" go back to the telescope dome, usually in the company of the night assistant, to complete their preparations. A final list of objects and "coordinates" is supplied to the telescope control computer. As the twilight fades and the sky becomes dark enough to work, the night assistant will "call up" the first object on the target list and a computer will instruct electrically driven motors on the telescope's rotation axes to slew to that position. Using a special video camera at the focus of the telescope, the guest astronomer examines the field of view to confirm that the telescope is pointing at the object of interest by reference to an existing star chart. Sometimes nothing can be seen because the object(s) are too faint and require a long exposure. In that case, the field must be confirmed by checking the pattern of brighter non-target objects in the vicinity. When the object is correctly centered, the observation begins. Having configured the camera or spectrograph to the required settings by using the instrument's control computer, all that is required next is to issue a "start" command. The total time for which the measurement lasts is called the "integration time" and this may be anything from a fraction of a second to hours depending on the brightness of the object, the efficiency of the instrument, the wavelength, and the nature of the experiment. If the integration time is long, then it is essential to ensure that the telescope continues to track the object very accurately. In principle, this can be done manually by viewing the object or a nearby star with the video camera, and pushing buttons on a "hand-set" connected to the telescope in such a way as to counteract any drift of the image. More likely, guiding will be performed automatically by the telescope control computer which will analyze the image of the guide star on the TV screen, compute any motion, and issue a correction to the drive motors of the telescope. When the exposure is complete, the image or spectrum will be displayed on a computer screen, an adjustment to the setting of the instrument might be made, and another exposure started. Meanwhile, some rapid analysis of the first result is carried out. This is crucial to the optimum use of telescope time.

The same pattern of work is repeated throughout the night. Nights can be long, from before dusk until well after dawn, typically 12 hours non-stop. Considerable concentration and often a degree of patience are required. Sometimes the latter is in relation to the other observers rather than with the experiment, and so some sustenance or "night lunch" might be taken on the job. Some look forward to opening up the little brown bag collected at dinner, others would just as soon not watch! Depending on how smoothly the experiment has progressed or on what has been found, tactical decisions may be required to optimize the use of the night. Certainly, as dawn approaches, an extra effort is made to get the most out of the remaining time. A golden rule of observing which many newcomers forget to follow is to assume that "every night is your last" and never leave a crucial measurement or calibration until tomorrow. Finally, with the last on-sky exposure complete, the night assistant will close the dome. A few more calibration frames are made and then the mirror covers are also closed and the telescope is returned to its parked position. At last the equipment is shut down or placed in standby mode, logbooks or fault reports are filled out, and the weary group rally round for the walk or drive back to the lodge. The observers sleep until early afternoon and then rise to prepare and review for the next night. Several days of this activity constitutes the "observing run". The visitors will then spend a few days at the offices of the observatory, perhaps to obtain electronic copies of their data and discuss their observations with local staff. Finally, they fly back to their home institute to analyze the astrophysical content of the data in detail and write a scientific paper.

If you plan to use single-dish radio telescope facilities then you may well follow the same pattern as optical and infrared astronomers, particularly for sub-millimeter observations. Interferometer and aperture synthesis telescopes such as the Very Large Array (VLA) near Socorro, New Mexico are too automated to have visiting astronomers present for interactive sessions. Usually, one submits an "observe" file and the observations are taken as part of a larger pre-programmed sequence. It may however be necessary for the astronomer to visit the facility during the data analysis phase to make use of computers and software not available at their home institute. Of course, the same process of competitive application for telescope time based on scientific merit is used. A similar situation is also encountered for telescopes located in space. While it may be necessary to visit the "home" institute of the satellite, such as the Space Telescope Science Institute in Baltimore (U.S.A.) or the Space Telescope European

Coordinating Facility near Munich (Germany), in the case of the Hubble Space Telescope, it is rarely necessary to visit the ground-station and operations center. Time on the Hubble Space Telescope and many other satellites is very competitive and is awarded in cycles on the basis of peer-reviewed scientific proposals. Once again, when time is awarded it is necessary to submit a detailed observing request that is programmed into a larger sequence by observatory staff. You will definitely not get to "play" with the telescope! Often, your data will simply arrive in the mail in electronic form, and usually in a form ready for you to begin scientific analysis.

Some ground-based observatories now operate a mode in which your observing request is carried out for you by observatory staff, and the execution is scheduled in such a way that your measurements are mixed in with those of other applicants. Your presence at the observatory is not needed. This approach can optimize the use of weather conditions, but tends to weaken the spontaneous response to a discovery that comes from being in control of the experiment. High-speed data links also make "remote observing" a real possibility, enabling the experiment to be controlled from a distant location. In fact, some telescopes are completely robotic (i.e., they are programmed to operate autonomously using weather stations and pre-programmed target lists). Of course, there are numerous privately owned observatories throughout the world, mostly associated with universities and research consortia. Some of these facilities are quite large, and others are fairly small. At many of these places there is a much greater degree of "do it yourself". Nevertheless, the pattern of preparation and work is essentially the same. Professional astronomers usually work in the comfort of a warm control room, rather than the dark and cold telescope dome, while electronic imaging devices and computer systems gather data. Occasionally, forays are made into the chilly mountain air outside to check on the weather or, as in my own case, simply to look up at the star-studded canopy of the night sky, marvel at its awe-inspiring beauty, and remind oneself that *this* is what it is all about!