Remote Sensing Tools for Exploration

Pamela Elizabeth Clark • Michael Lee Rilee

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Observing and Interpreting the Electromagnetic Spectrum

Springer

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ISBN 978-1-4419-6829-6 e-ISBN 978-1-4419-6830-2
DOI 10.1007/978-1-4419-6830-2
Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2010930510

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

This book is dedicated to our colleagues-scientists, engineers, technicians, and program managers-who work hard to develop remote sensing missions, particularly those beyond Earth orbit with minimal resources. We honor their innovation, clever design of instruments and spacecraft, and ability to obtain viable results, even when they must use only available technology to minimize mass, power, volume, and bandwidth. We also recognize that we stand on the shoulders of those pioneers in remote sensing who have written on the subject, and owe a special debt of gratitude to Nick Short, Paul Lowman, Floyd Sabins, Steve Curtis, Charles Elachi, Barry Siegal, Alan Gillespie, Isidore Adler, and Jack Trombka.

Preface

Remote Sensing from a New Perspective

The idea for this book began many years ago, when I was asked to teach a course on remote sensing. Not long before that time, I had been part of the effort to develop the first database for planetary data with a common digital array format and interactive processing capabilities to correlate those data easily: the lunar consortium. All the available lunar remote sensing data were included, orbital and ground-based, ranging across the entire electromagnetic spectrum. I had used this powerful tool extensively, and, in that spirit, I was determined to create a course which covered the entire spectrum and a variety of targets. As I looked around for the equivalent of a textbook, which I was willing to pull together from several sources, I realized that available material was very heavily focused on the visual and near visual spectrum and on the Earth as a target. Even *The Surveillant Science*, edited by Edward Holz and published in 1973, which broke new ground in having diverse articles on most of the spectrum when it was created, focused entirely on the Earth. My personal favorite, the exceedingly well written book on remote sensing by Floyd Sabins first published in 1978, covered the visual, infrared, and microwave portions of the spectrum beautifully but focused on the Earth as well.

Unhindered, I developed what I called 'packets' of material for each part of the spectrum. My background in remote sensing, which was unusual at that time, involved the high energy portion of the spectrum. This proved complementary and essential to the effort. I knew my sources there well and had been involved in creating many of them. Because we had worked hard to establish the credibility of orbital X-ray and Gamma-ray remote sensing, I was also well aware of the need for data fusion, the combining of data from different portions of the spectrum to constrain and improve interpretations beyond what could be accomplished with one dataset. Establishing quantifiable links between geochemical signatures and geological features was an important part of the work.

In the years that followed the development of that remote sensing course, I have become more involved in instrument development and science planning for a variety of targets in the inner solar system. In providing support for mandated efforts to return humans to the Moon and Mars, I have come to appreciate the importance of creating a good working relationship between those representing science, engineering, and technology efforts. I have come to view remote sensing as a process, in the context of concept development, implementation, and operation.

Thus, among the constellation of books on remote sensing, what this book has to offer is that holistic view. Remote Sensing Tools for Exploration is designed to create common ground for all of those, including scientists of different disciplines as well as engineers, technicians, and managers, who will be involved in bringing remote sensing instruments and missions to fruition. As part of this effort, we are also creating an interactive website where any aspect of remote sensing can be discussed and tools for any aspect of remote sensing may be shared. In this way, we hope to facilitate breakthroughs in remote sensing.

I have asked my colleague of many years, Mike Rilee, to join me in this endeavor. We will be harnessing has background, complementary to mine, in the areas of computer science and fields and particles. He will be principally involved in creating and updating our website.

The organization scheme of the book is as follows. Introductory chapters give the context for remote sensing experiments. Chapter 1 describes the preliminary planning and supporting systems for a remote sensing mission. Chapter 2 provides overall principles of remote sensing science and an overview of the electromagnetic spectrum. The body of the book is logically based on major divisions in the electromagnetic spectrum, including Chapters 3 (Visible and Circumvisible Region and Image Interpretation), 4 (The Ray Region), and 5 (The Longwave Region). Treatment for remote sensing data in its various forms and stages of processing (e.g., data strings, images, 3D models) are discussed in the final chapters on Data Processing and Data Fusion. Although we may not be able to include them in this version of the book, in future editions we will include a chapters on fields and particle to describe the nature, treatment, and instrumentation for in situ measurements, and on instrument and spacecraft support systems.

Pamela E. Clark
NASA/GSFC
April, 2009

About the Authors

Pamela Elizabeth Clark

Pamela E. Clark, PhD, grew up in New England and, inspired by President John Kennedy, decided to explore outer space by the time she was thirteen years old. She thought, “If they can put a man on the moon, they can put a woman (me) on Mars!” She obtained her BA from St. Joseph College. There, she had many opportunities to participate in laboratory research with Sr. Chlorophyll (Dr. Claire Markham) and Sr. Moon Rock (Dr. Mary Ellen Murphy) as well as to coordinate an NSF inter–disciplinary undergraduate field research project. While obtaining her PhD in planetary geochemistry from the University of Maryland, she worked at NASA/GSFC outside of Washington DC and the Astrogeology Branch of the USGS in Flagstaff, Arizona, simulating, analyzing, correlating, and interpreting lunar X-ray spectra. She was a member of the group, led by Isidore Adler and Jack Trombka, that pioneered the use of orbital x-ray and gamma-ray spectrometers to determine the composition of planetary surfaces. She participated in the Flagstaff Lunar Data Consortium, the first attempt to create a common format database for all the remote sensing data from a planetary body. After completing her PhD, she joined the technical staff at NASA/JPL , worked with the Goldstone Solar System Radar group, and expanded her remote sensing background to include radar, thermal and near infrared studies of planetary surfaces with particular emphasis on the study of Mercury’s surface. Dr. Clark organized a briefing team to promote a mission to Mercury, and for awhile edited the Mercury Messenger newsletter. Springer recently published her book “Dynamic Planet: Mercury in the Context of its Environment.” She eventually returned to Goddard to work with the XGRS team on the NEAR mission to asteroid Eros. Dr. Clark is the science lead in a group initiated by Steve Curtis to develop new paradigms for the design of space missions and vehicles. She is currently involved in developing and evaluating surface science scenarios, tools, technologies, and architectures and for space missions to extreme environments, with particular emphasis on the Moon and Mars. Dr. Clark has done several stints in academic institutions, including Murray State University in Kentucky, Albright College in Reading, Pennsylvania, and Catholic University in Washington DC. She has developed courses in analytical and environmental chemistry, geochemistry, physical geology, mineralogy, optics, planetary astronomy, remote sensing, and physics. Her major goals in life include exploring under every rock to increase the sense of wonder about the solar system.

Michael Lee Rilee

Michael L. Rilee, Ph.D., is the founder of Rilee Systems Technologies LLC which focuses on advanced computing technologies for autonomous aerospace and robotics applications. Rilee is a plasma physicist and astronomer by training with experience in high-performance computing as applied to ground and space-based systems. He was a key researcher in NASA Goddard Space Flight Center's parallel and distributed robotics efforts, including Tetrahedral Robotics.

Contents

Chapter 1
An Overview

1.1 What is Remote Sensing?

Remote sensing is a multi-faceted and multi-disciplinary endeavor to acquire information from remote targets, via ground-based, orbital, aerial, or remote in situ sensors, involving the following tasks, shown schematically in **Figure 1.1**:

1) developing a mission and designing a spacecraft and/or instruments to operate within the constraints of that mission to characterize a target remote from the investigator in the context of its surrounding environment.
2) using instrument(s) to detect, acquire, and calibrate data from selected regions of the electromagnetic spectrum being produced at the target.
3) transmitting data collected and encoded on an electromagnetic carrier signal, then receiving and decoding the signal at the investigator's location, requiring knowledge of the spacecraft position and instrument orientation relative to the target.
4) analyzing and interpreting data potentially involving statistical analysis, mapping, and field work as well as sample analysis to provide *ground truth* or reference.
5) archiving and managing the data thus obtained for scientific and public users.

Obviously, even an individual with great capability for *multi-tasking* cannot perform all of these tasks essential for obtaining useful remote sensing measurements. Remote sensing is accomplished through team efforts of those with a wide variety of technical skills, including computer scientists, aerospace engineers, and geoscientists, to name a few. Typically, until operating in a space venue becomes routine, these efforts are supported by ongoing projects funded through national and international space exploration organizations, such as NASA, ESA, and JAXA.

1.1 Close to Home: Dealing with unanticipated challenges. *Perhaps, when many people envision space mission teamwork, they envision NASA ground crew response during Apollo 13, as fairly accurately illustrated in the scenes from the movie on the mission (Universal Pictures 1995). The movie implies that everyone involved in the Apollo mission, including astronauts as well as investigators who*

P.E. Clark, M.L. Rilee, *Remote Sensing Tools for Exploration*,
DOI 10.1007/978–1–4419–6830–2_1,

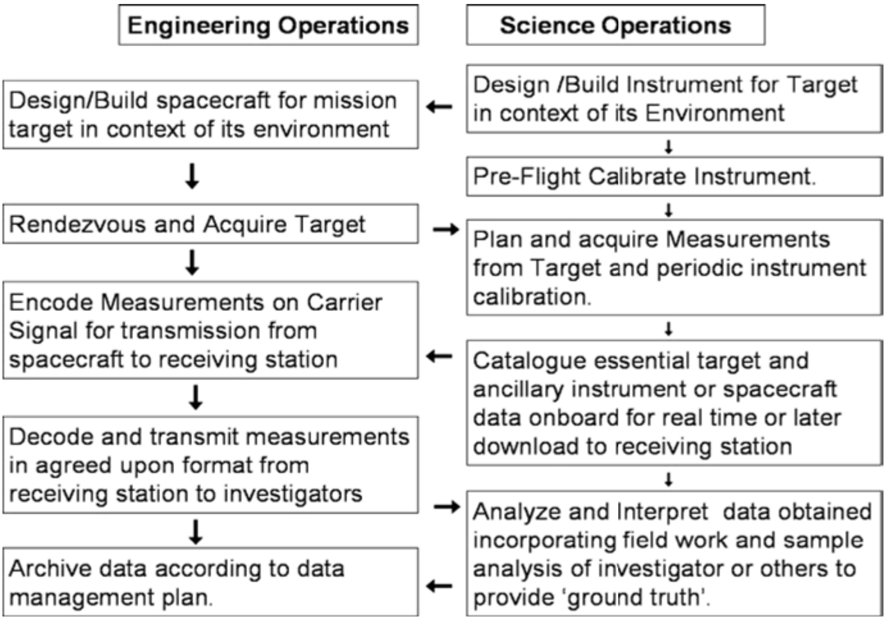

Figure 1.1 Remote Sensing as a multi-step, multi–discipline endeavor.

supplied the remote sensing instruments, were trained via simulations of potential disasters. Of course, such training developed the capability to think outside of the box as well as to overcome the tendency to panic. Everyone (engineers from a variety of disciplines, mathematicians, computer programmers, instrument providers, lunar scientists, mission controllers, astronauts) brought their combined expertise to the table to figure out a way to interpret conflicting telemetry readings and filter carbon dioxide form the crew compartment. On other Apollo missions, such problems ranged from overcoming failure modes on spacecraft computers, to dealing with unanticipated dust accumulation on the lunar rover. However, this kind of teamwork begins much earlier, during mission planning and instrument development. For example, recently, we brought a generic design concept for a lunar surface instrument package designed to monitor the lunar environment, over to the instrument and mission development labs at Goddard Space Flight Center (GSFC) to perform a typical week long run to develop an integrated design and requirements. The labs act as tiger teams, with engineers from a variety of disciplines and scientists from the team solving design challenges as they come up during the run. Our major challenge was designing a power system of sufficiently low mass that could survive the lunar night. Power was to be provided by solar panels and batteries. The Pu238 based radio thermal generators used during the Apollo missions, capable of providing thermal support as well as power, are not guaranteed to be available. We brought together a special multi-disciplinary team who are now developing a multi-faceted strategy including elements such as ultra low *power and ultra low temperature electronics, managed power, and alternative thermal systems.*

1.2 The Roots of Remote Sensing

Remote sensing as an identified field is most frequently associated with *geoscience* applications, ranging from the earliest aerial photographic surveillance to deep space flyby or orbital exploration. Such applications have shaped our approach to studying and understanding solid surfaces (e.g., Sabins 1996; Elachi and van Zyl 2006; Siegal and Gillespie 1980; Short 2007; Lillesand et al. 2003). That being said, the first de facto remote sensing specialists were actually astronomers, who studied targets, gaseous and solid, remote from the Earth. In fact, the twentieth century, particularly from the time NASA was created by the National Space Act in 1957, has seen the rapid proliferation of and access to instruments and carriers for instruments (spacecraft) in a range of venues (landers, orbiters), and data handling techniques at steadily decreasing cost for civilian or commercial use (Launius and Jenkins, 2002). Now, the boundaries are blurry. Scientists study the surfaces of planets from Earth-based observatories (e.g., Jensen 2006; Campbell 2006) or from landed in situ instruments (e.g., Sabins 1996; Short 2007). Orbital platforms are used to study the fields and particles environments around Earth and other planets. Planetary interiors, crusts and oceans, atmospheres and magnetospheres, can be studied from a variety of platforms in locations ranging from the ocean floor to deep space (e.g., Short 2007). Finally, we can begin to understand the Earth in its true context.

Many of the more significant contributions to the field of remote sensing have been direct benefits of the early space program (Launius and Jenkins 2002). Successful accomplishment of orbital and then deep space operations required robust, dependable systems that could perform as autonomously as possible with minimal mass, power, and communication resources. NASA engineers and scientists were thus strongly motivated to extend the *state of the art* to its limits in the development of high resolution sensors, rugged but lightweight hardware, responsive and predictable software, and progressively more sophisticated robotics. With these tactics, they could promote the strategy of minimizing the resources for the growing number of operational missions that were increasing in complexity and distance to target. In fact, the space program has been a major source of innovative technologies for the civilians sector since the 1960’s (Launius and Jenkins 2002), in telemetry (remote monitoring), aeronautics, biomedical advances, new materials, personal electronics, to name just a few areas of development. We are not exaggerating when we say that detailed exploration of the Earth and solar system in previously inaccessible places has revolutionized our context for understanding the Earth and led to new paradigms for the origin of the solar system (Wood 1999).

Pre-NASA Technological Milestones in Remote Sensing

Time	Development	Example
1830's	First Recordable Photography	First camera with Film (Daguerrotype) 1835
1840's	First Use of Photography in Astronomy	First Image on Photographic Plate 1840
1890-1910	First Camera for Aerial Reconnaissance	First Image from small rocket launch 1897
1900-1910	Direct Color Photography	First Autochrome (Color Photo from one film) 1903
1930's	Sonar and Radar	Radar Experiment Feasibility Sketch, 1929
1930's	Automated Colorimetry	First Spectrophotometer (Beckman)1940
1930's	First High Velocity Rockets	Rocket in launch assembly (Goddard) 1935
1940's	First SubOrbital Launches	Nazi V2 1945
1950's	First Orbital Payload	Sputnik 1957

Figure 1.2 Pre-NASA Milestones in Remote Sensing.

The history of remote sensing science as we have technically defined it is relatively short in terms of all of human history (**Figure 1.2**). It began in the 19th century with the development of photography (Leggat 1995), a crucial component for the recording of remote observations. Soon after the camera was applied to the scientific study of human activities, cameras were mounted in telescopes to record photographic images of the sky allowing higher precision, quantitative study of the behavior of celestial objects (Crawford 2007). Cameras were also mounted on balloons in the mid-1800's, and by the turn of the century on kites and carrier pigeons as the camera became smaller and more automated (Short 2007). It didn't take the inventors of the airplane long to realize the value of aerial reconnaissance, resulting in the first aerial images of human and natural landscapes during World

Early NASA Technological Milestones in Remote Sensing

1958	US First Orbital Payload Launch	Explorer
1960	First Communication Satellite	Echo
	First Weather Satellite	Tiros
1961	US First human sub-orbital flight	Mercury (Shepard)
1962	US First human orbital flight	Mercury (Glenn)
1964	First Close-up Images of lunar surface	Ranger 6-9
1966	First Orbiter of Another Body First Systematic Orbital Photography	Lunar Orbiter 1-5
1966	US first Soft Lander on another body	Lunar Surveyor
1969	First human orbiting and landing on Moon First orbital remote sensing of another body First in situ observations of another body First systematic sampling of another body	Apollo 11
1972	First systematic orbital coverage of Earth	ERTS

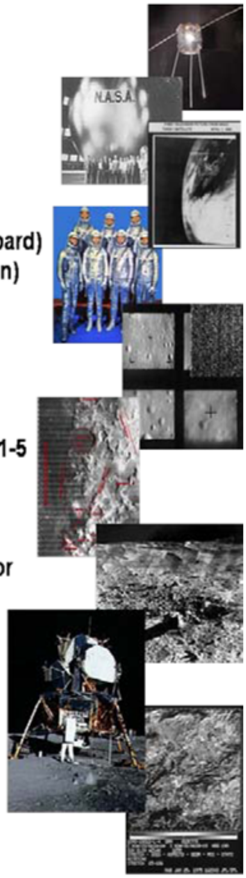

Figure 1.3 Early NASA Milestones in Remote Sensing.

War I (Short 2007). The 1930's saw the development of color photography, as well as two kinds of instruments capable of detecting and determining the distance to remote targets, radar on land and sonar under water (Coe 1978). Both were applied during World War II. At about the same time, the development of instruments called spectrophotometers allowed the recording of spectra in the visible region: intensity of light received from a target as a function of energy, the quantitative recording of *color* (Simoni et al. 2003). The drive was on to develop spectrometers for standardized and routine use in laboratories as well as for other parts of the spectrum. Immediately after World War II, a poorly coordinated attempt was made to launch America into the *Space Age*. We recruited the German scientists who had sub-orbital flight experience gained in building the V2s to develop a rocketry program of our own. The American program was beset by technical problems aggravated by inter–service rivalry problems. Then, when the National Space

Act of 1958 created NASA in response to the Soviet launch of Sputnik, the US space program was literally off the ground in short order with the successful launch of the Explorer and Vanguard satellites.

In the ensuing decade, our technological milestones (**Figure 1.3**) included human sub-orbital and orbital flights, docking in space, landing a spacecraft on another body, the first deep space navigation and communication capability to support deep space robotic and human operations, the first systematic orbiting of, imaging of (Lunar Orbiter), and landing on (Ranger, Lunar Surveyor) another body, and the first human landing on another body (Hall 1977; Byers 1977). Why are we mentioning all of these technology milestones in a book on remote sensing? Because all of these technologies laid the foundation for *remote sensing* as we know it, creating the capability to rendezvous with, fly by, land on, or orbit around targets in the solar system, many of them without atmosphere to attenuate the signals from targets.

Since that time, decades ago, instrument, mission, and detector designs have proliferated to fill the greatly expanded number of niches accessible for exploration (**Figure 1.4**). The Apollo program itself saw the deployment of the widest range of orbital remote sensing instruments ever flown, including the first orbital X-ray and Gamma-ray detectors for determining composition, a laser altimeter for obtaining topography, a magnetometer to measure magnetic field variations, as well as a wide range of in situ instruments to measure the interior and exterior environment of the Moon long after the astronauts departed. With the advent of the terrestrial satellite program, based on developments in automated color photography initiated from the early sixties for the Mercury, Gemini, and Apollo missions (Swenson et al. 1999; Hacker and Grimwood 2002; Compton 1989), more sophisticated imaging systems recorded color images of visual and near visual (UV, IR) energy bands for the ERTS and LANDSAT programs and eventually mid to far IR energy bands for follow-on terrestrial application programs. Within three decades after NASA inaugurated the terrestrial remote sensing program, the infrastructure has been developed, thanks to the wise investment by the American people, and terrestrial orbital operations have been made routine and economically viable for private investors. The use of more sensitive instruments for ground-based observations have also greatly improved our ability to characterize distant targets in terms of properties not dreamed of in the early days of remote sensing, for example, surface roughness, average slope, ice detection (radar), or atmospheric constituents (UV).

What kind of remote sensing missions has NASA been launching (**Figure 1.4**) during the last decades? This list does not include missions launched by other countries, American government agencies, or private corporations (such as weather satellites launched by NOAA). Even so, by far the largest number of NASA launches to a single target have been Earth orbital missions. Missions of this kind have become routine. Because they require relatively little in the way of expendables, such as fuel, to reach their destinations, scientific payloads can be larger.

NASA and NASA Collaborative Post-Apollo Robotic Missions		
Inner Solar System	**Outer Solar System**	**Earth (Recent)**
Clementine (Moon) 1994	Pioneers 10, 11 (Jupiter Saturn) 1972-	SeaWiFS 1997
Lunar Prospector 1998	Voyagers 1, 2 1977-	TRMM 1997
Lunar Reconnaissance Orbiter 2008	Galileo 1989-2003	Landsat 7 1999
Mariners 2, 5, 10 Venus/Mercury 1962-74	New Horizons 2006	QuickSCAT (SeaWinds) 1999
Messenger (Mercury) 2008-2011	Juno 2010	Terra 1999
Pioneer Venus 1978-92	Cassini-Huygens 1997-2005	ACRIMSAT 1999
Magellan (Venus) 1990-94	Neptune Orbiter 2016	Eo-1 2000
Mariners 4, 6, 7, 9 Mars 1965-7		Jason 2001
Vikings 1, 2 (Mars) 1976	**Sun**	Meteor-3M (SAGE III) 2001
Mars Pathfinder 1997	Solar Maximum Mission 1980-89	Aqua 2002
Mars Global Surveyor 1997-2006	SOHO 1995-	ADEOS II (SeaWinds) 2002
Mars Odyssey 2001	Ulysses 1990-	GRACE 2002
Mars Exploration Rovers 2004-	STEREO 2006-	ICESat 2003
Mars Reconnaissance Orbiter 2006-	Solar Dynamics Observatory 2008	SORCE 2003
Phoenix Lander (Mars) 2008		Aura 2004
Mars Science Laboratory 2009	**Space Observatories**	UARS 1991-2005
Mars Scout 3 2018	Hubble Space Telescope 1990-	CALIPSO 2006
Mars Sample Return Missions 2016-24	Compton Gamma-ray 1991-2000	THEMIS 2007-
	Chandra X-ray 1999-	TIMED 2007
Asteroids/Comets/Inter-Planetary	Spitzer Space Telescope 2003-	OSTIM 2008
Pioneers 6, 7, 8, 9 1965-68	Cosmic Background Explorer 1989-93	Glory 2008
NEAR 2000-2001	FarUV Spectroscopic Explorer 1999-2007	OCO 2008
Deep Space 1 1998-2001	Infrared Astronomical Satellite 1983	Aquarius 2009
Deep Impact 2005	Wilkinson μwave Anisotropy Probe 2001-	NPP 2009
Stardust 1999-2006	Xray Explorer Satellite 1970-73	LDCM 2011
Dawn 2007-2015	HEAO-1 1977-79	
	HEAO-2 (Einstein Observatory) 1978--80	
	James Webb Space Telescope 2013	

Figure 1.4 NASA and NASA Collaborative Missions during the last 50 years.

Our planet's changing environment, its atmosphere, hydrosphere, and land are the subject's of tremendous interest. These data have immediate practical application for monitoring trends in climate change, agriculture, movements of water, ice, and vegetation, geological activity and even human activity (such as large-scale burning). We have sent the missions to the Sun for the same reason, to monitor its activity and the way it affects our environment. Other missions, at first flybys and then orbiting mapper missions, have been sent first to the inner and then to the outer planets. Mars, a planet that could have fostered life at one time, is the target of more than half of the missions to the inner solar system. In the course of this book, we will illustrate the nature of data from each spectral region using examples of observations taken by these missions.

1.2 Close to Home: Case Notes for two Pre-Apollo programs. *The Ranger and Lunar Orbiter programs, both essential robotic precursors to the Apollo Program, represent* ***end members*** *for mission development profiles. Why? As the first series of missions planned for an extraterrestrial target, the Ranger Program faced major technological challenges, including operational complexity (with imager, hard lander, and initially penetrator), and establishment of systems required for all remote sensing missions to come (including remote navigation, tracking, communication, and spacecraft component automation). These challenges eventually were met despite frequent changes in design of major components and mission concept, as the stated capabilities of the Air Force supplied launch vehicle shifted dramatically. Disagreements arose within the science community over priorities for* ***sky*** *as opposed to* ***planet*** *science, within the aerospace community over control (civilian versus military) and management style (loose academic versus tight industrial). These conditions resulted in a pattern of major setbacks and creative recoveries, as well as delays and increased costs. Close-up imaging of the surface became the primary and then the only* ***science*** *focus and set the stage for the major role and importance of imaging on future missions. On the other hand, Lunar Orbiter became the* ***poster child*** *for a successful mission, coming in within budget and time guidelines, and providing the basis for selecting and planning activities at Apollo landing sites. The struggles of Ranger became lessons learned that could be applied to Orbiter, including far better definition and control of project activities and costs from the beginning. Major challenges were the short time frame and limited budget available, as well as the development of the orbital camera system. New technology had to be invented for image capture, production, and transmission, yet still resulted in relatively small penalties in time and cost.*

1.3 Physical Principles of Remote Sensing

An underlying assumption in remote sensing is that remote targets of interest have characteristic energy *fingerprints*, identifiable on the basis of sufficient spectral (energy) resolution (depending on the nature of the signal) and spatial resolu-

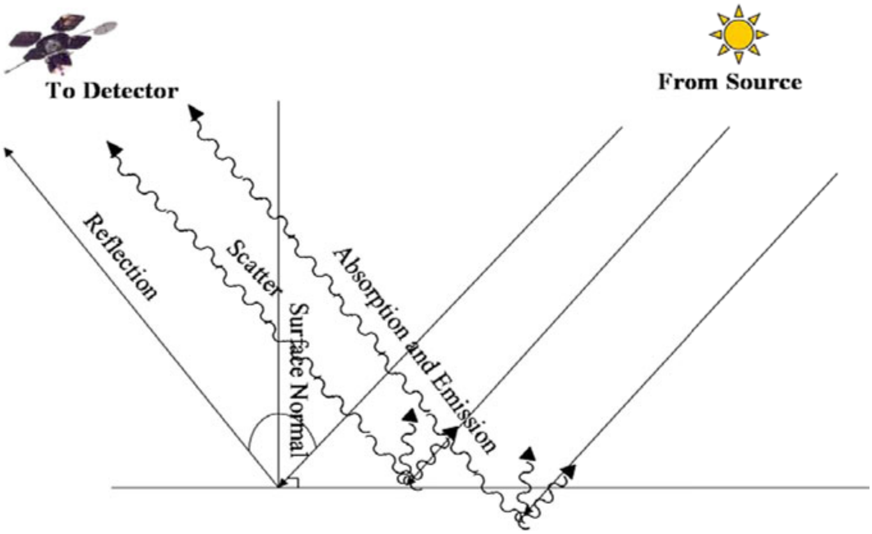

Figure 1.5 Energy Flow from source to target to detector involving elastic and inelastic energy transitions at the target.

tion (depending on the size and nature of variation of the target). What can act as a source? How does a target *generate* a signal? How does that signal get recorded? General principles are discussed here. Details for each spectral region will be discussed as appropriate in later chapters of the book.

Figure 1.5 is a schematic showing the flow of energy from source to investigator. A source, normally a natural one and not the instrument itself, generates an energy spectrum. When the instrument itself generates a signal that interacts with the target, the process becomes active rather than passive remote sensing. Energy interacts with a target to generate a signal in any or all of the following ways:

1) Reflection, coherent scatter, or transmittance, processes in which energy transfer is completely elastic though it can vary in efficiency
2) Absorption and reemission at lower energy (inelastic energy transfer) through discrete processes such as reflectance band generation (Near IR), fluorescence (X-ray or UV), photoelectric emission (X-ray), inelastic line generation (Gamma-ray), incoherent or Compton scatter, or continuous processes such as black body radiation emission. (These mechanisms will be described in detail in the chapters on each spectral region.)

The transfer of energy from the source to the target to detector is captured simply in *Equations 1.1 and 1.2*:

$$E_{observed} = E_{source} - E_{target} \tag{1.1}$$

Experimental Conditions	
Environmental Conditions	**Instrument Operation**
Temperature Extremes and Variations	Thermal Design Active or Passive Heating or Cooling
Pressure Extremes, Variations	Mechanical Design
Attenuation by Atmosphere, Aerosol, Dust	Increase Detector Sensitivity, Spectral Resolution, Integration Time Determine depth of penetration, detection limit
Source characteristics Variability, Illumination	Monitor Source, Increase Integration Time, Fill Field of View with Smallest Footprint, Nadir Pointing, Optimizing Spatial Resolution
Viewing geometry	Provide Collimation for Instrument, Fill Field of View with Smallest Footprint, Nadir Pointing, Optimizing Spatial Resolution
Target Variations in Texture, Composition	Increase Detector Sensitivity, Spectral Resolution, Signal to Noise Ratio To Minimize Integration Time and Increase effective Spatial Resolution

Figure 1.6 Matching Operational Requirements with the environmental constraints.

$$E_{target} = E_{absorption} - E_{scattering} - E_{emission} + E_{transmission} \qquad (1.2)$$

Many users of remote sensing data are interested only in the final data products for a particular application. For these workers, prior steps may appear to be a *black box*. This book will open that box, and illustrate the extraordinary challenges and resulting breakthroughs involved in observing and recording processes in their complex natural settings rather than under the controlled environment of a laboratory. Such study requires the development of techniques that allow comprehensible models to be derived from the apparent chaos of nature. In this way, remote sensing is both art and science.

Energy Transfer Process: Remote sensing assumes the presence of a source, a target, and a detector (**Figure 1.5**). Energy from a source impinges on a target, and the resulting *energy production* process depends on the energy spectrum of the source and the compositional and physical nature of the target. A portion of that energy is absorbed into or transmitted through the target. Another portion interacts *elastically* with the target, coherently scattered at or near its surface, with the nature and direction of that reflection depending on the physical nature of the target on the scale of the wavelength. If a target is relatively rough on the scale of the wavelength, diffuse reflection, with no preferred direction, occurs. For a target smooth on the scale of the wavelength, specular reflection, with a preferred direction, occurs. Another portion interacts *inelastically*, with absorption and reemission at a lower energy. Higher energies induce characteristic electronic or molecular energy transitions, resulting in characteristic energy output in the form of discrete narrow lines or wider bands. At lower energies, the reemission may be continuous, as in black body radiation, yielding a continuous spectrum characteristic of temperature.

Environmental conditions: The environment (**Figure 1.6**) in which an interaction is being measured can have considerable impact. Temperature and pressure can influence the state of the target, efficiency of the energy transfer process occurring there, as well as the operation of the detector system. If an atmosphere of any kind is present, attenuation will occur in many energy regimes, correlated with the path length of the signal through the atmosphere, and preclude some or all observations in that part of the spectrum. For example, the Earth's atmosphere attenuates X-ray lines over distances required for remote sensing experiments.

Sources: Unless an active remote sensing technique is being used, whereby the instrument acts as the source transmitting a signal, a natural source is required to be sufficiently active or intense to stimulate signal production in the target. The location and nature of the source has consequences. The use of a natural source, otherwise known as a passive remote sensing technique, may require the addition of a *source monitor* if the source spectrum varies significantly. Using a natural source always requires the establishment of the source/target geometries each time a measurement is made. The source intensity decreases as a function of both the inverse square of the distance between source and target and its angle of incidence or departure from the surface normal (directly overhead). Although not always practical, the use of an active source, when the target is remote from the spacecraft, increases power and mass requirements.

Detection: Detectors, which will be discussed in detail for each energy region, operate by separating and measuring component intensities, from which abundances can be derived, either physically or spectrally. Physical dispersion systems include mass spectrometers or particle analyzers that separate vaporized or ionized components on the basis of their mass and charge. Spectral separation of signal into constituent *bins* is done on the basis of wavelength or energy. Optical detectors include photosensitive surfaces for creation of images, such as CCDs, and spectrometers with wavelength and energy dispersive systems. Wavelength dispersive detector systems use the principle of diffraction or even refraction, to separate incoming signal on the basis of wavelength, like a prism separating white light into its color components. Energy dispersive systems convert input signals into pulses with intensities proportional to input signal energy, in sensitive *proportional counting* devices, most recently made of solid state media. Thermal detectors use temperature sensitive devices, such as thermocouples or thermistors.

Adequate resolution is necessary to resolve discrete features spectrally and spatially. Detectors vary in their ability to perform this separation, as measured by their inherent spectral resolution and sensitivity, as a function of energy regime and operational environment. Spectral resolution is achieved by energy dispersion (as in pulse height analysis) or wavelength (physical) dispersion (as in grating or

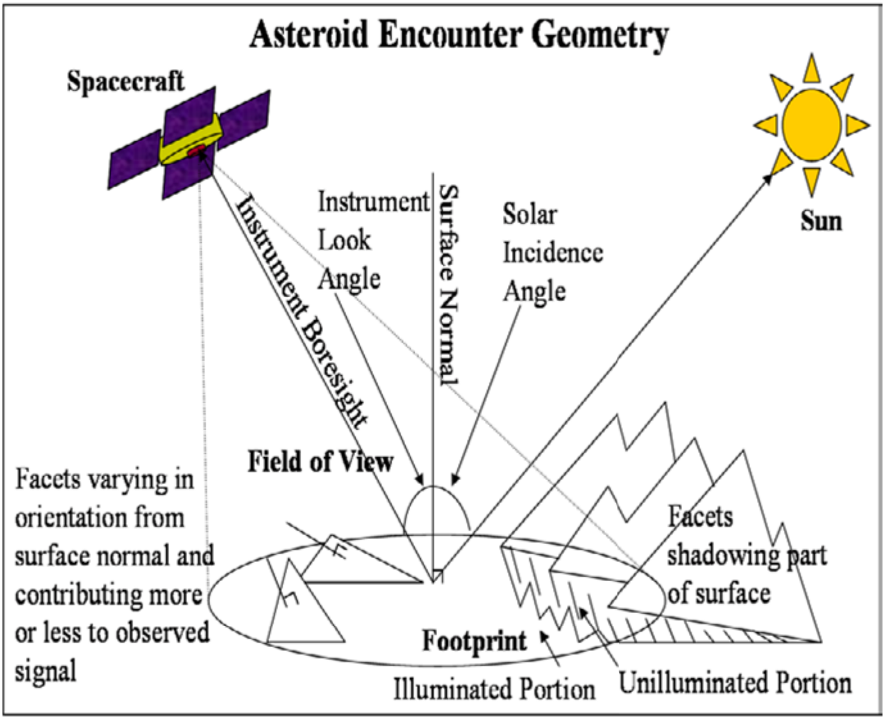

Figure 1.7 Complex viewing geometries resulting from constantly changing frames of reference of source, target surface, and instrument, particularly for target rough on the scale of the instrument field of view.

dispersion optics) processes. In some cases, the incoming signal must be focused to increase the signal to noise ratio (as with a dish antenna or collimating fiber optics). The field of view is spatially limited, to achieve an acceptable spatial resolution, through optical collimation. A nadir pointing instrument is ideal for most mapping applications, but can't always be achieved. Oblique pointing will increase the size of the footprint. The efficiency and sensitivity of a detector as a function of energy and angular position in the field of view must be determined as part of the calibration process as well.

Careful calibration of the detector system using sources of known composition, targets of known characteristics, and, as much as possible, simulated measurement conditions before flight, will help to establish the accuracy and the precision of the measurements. The results will be incorporated into the design of the hardware and analysis systems. Without such data, derivation of *absolute* measurements, difficult under the best of circumstances, will be hopeless and even the establishment of the nature of *relative variation* criteria will be difficult. In-flight calibration methods should also be established, as a way to monitor instrument performance and compensate for any degradation occurring over time.

Careful modeling of anticipated energy production under operational conditions must go into design of the detector system before the instrument is built. The selection of a detector collimation angle is critical here. If it is too large relative to the intensity of signal coming from the target, the field of view may not be filled and the effective spatial resolution may be considerably degraded. If it is too small, the instrument may be pointing off into empty space frequently, the integration times required to achieve a sufficient signal to noise ratio long, and the target/detector geometries may vary considerably, making analysis difficult and degrading effective spatial resolution.

Measurement system geometries: Source/target/detector geometries are trivial in a fixed setting either in the laboratory or in the field (in situ), but not for cases where the target is remote from detector. The frame of reference for the detector, Sun, and target relative to instrument pointing is constantly varying (**Figure 1.7**). Spacecraft navigation parameters must accompany each measurement as ancillary data essential for the interpretation of the measurement. The geometries may become complex, the target may or may not fill the field of view, and the size and shape of the footprint may vary considerably, particularly if the target is *rough* on the scale of the field of view. The increase in take-off angle, or departure of the spacecraft from nadir pointing, will decrease the effective spatial resolution, due to the greater size of the footprint. In cases of extreme roughness on the scale of the footprint, as in the case of the NEAR asteroid orbiter, it was necessary to model the footprint area as a cluster of facets with assigned areas and offsets from *normal* and then to deconvolve the observed signal on that basis.

Mission Style: Measurement system geometries are quite different, depending on the nature of the mission plan. The easiest mission is the *flyby* whereby a spacecraft brings a payload into the vicinity of an object, performing a rendezvous, possibly getting quite close, without going into orbit around it. One advantage of this approach is that relatively little fuel is required, and thus science payloads can be larger. Orbital insertion, requiring fuel, is required for the orbital missions desirable for mapping a large portion of a body over a period of time when most if it will have been illuminated for visual imaging. Of course, nearly all Earth application missions are orbiters. Probes, or penetrators, may descend directly from a ballistic trajectory through the atmosphere or to the surface, but are more often launched from an orbiter. Their landings are essentially *hard* or uncontrolled, as opposed to those of landers or rovers, which are controlled or *soft*. Obviously, a soft landing requires more fuel, translating into a smaller payload or a larger launch vehicle to generate more thrust along a trajectory from Earth.

Targets: Depending on its composition and environmental conditions, a target may be solid, typical for geological or biological applications of remote sensing; liquid, as in oceanographic applications; gas, as in atmospheric applications; or plasma (energetic electrons or ions) as in the study of fields and particles. As the temperature increases, the intrinsic heat or enthalpy of a material increases, resulting in greater degrees of freedom for individual particles, accompanied by changes from solid to liquid to gas to plasma and different energy transfer processes. Thus,

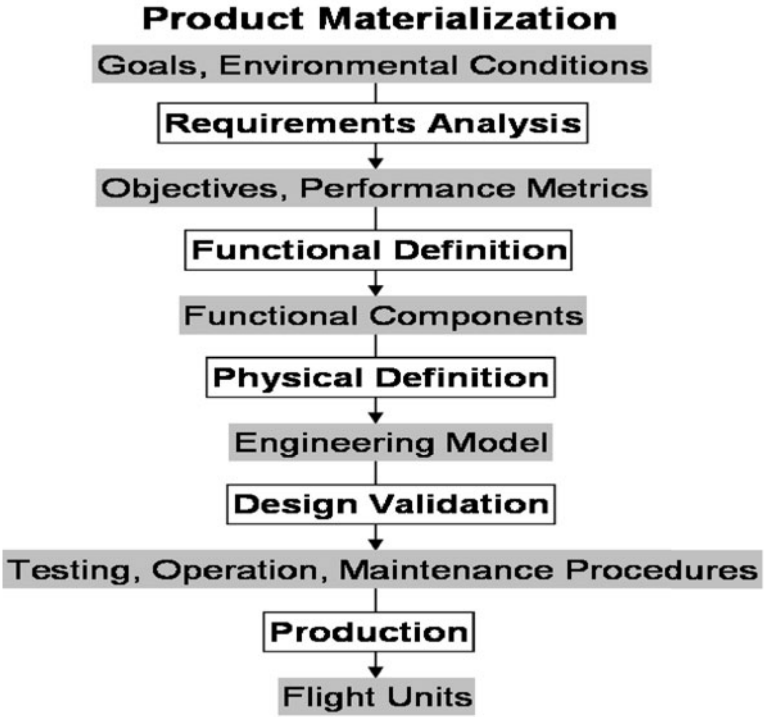

Figure 1.8 Product Materialization process, the application of the scientific method to engineering a complex system.

different spectral regimes and detector systems are appropriate for different environmental regimes. Consider the variety of detectable properties associated with water in a range of states which might be measured: detection of water vapor in an atmosphere (characteristic vibrational modes of a gas detectable in the mid-IR), detection of liquid water or ice in the ground (increase in dielectric constant detectable by ground-penetrating radar), or properties of a liquid ocean (visible or near visible reflectivity variations as a function of composition and temperature), or protons from dissociated water (particle analyzer).

Another consideration is the depth of penetration into a target as a function of wavelength. Generally, the larger the wavelength, the greater the depth of penetration, with the exception of the Gamma-ray region, where the depth of penetration is on the order of tens of centimeters compared to tens of microns for the X-ray region.

1.4 Systems Approach to Remote Sensing

Present day remote sensing projects have evolved into exceedingly complex data generation systems: each mission operates under a range of conditions and produces data from a variety of sources, from instruments in the science payload and from spacecraft systems that support the payload. The complex interactions of a mission, involving teams with many different disciplines, must be guided and managed. Complex systems of a spacecraft must be designed, built, operated, and maintained. Signals must be detected, transmitted, stored, and ultimately transformed into data products. Each area of expertise necessary to accomplish these tasks, including science, engineering, and mathematics disciplines, has its own special language and methodology. The challenging task of bridging the gaps between specialties is provided through systems engineering (NASA Office of Chief Engineer 2007, 2008; Kossiakoff and Sweet 2003) performed by motivated and experienced scientists or engineers with instrument development experience. Such individuals can provide a breadth of multidisciplinary knowledge and experience and a firm commitment to mission success.

Systems engineering came into its own as a discipline (Kossiakoff and Sweet 2003) after World War II. Advances in technology, particularly in the areas of automation and high speed computing, combined with greatly increased government funding for research and development, made possible the development of complex systems that could perform in the remote environment of space. The demand for more specialized and higher resolution remote sensing hardware, software, and data led to the need for greater resources for planning and development of compatible interfaces. To do this, systems engineering, when done properly, incorporates extensive planning and documentation with the innovation essential for proper project management in order to insure that mission development and operational requirements are met (Kossiakoff and Sweet 2003). Systems engineering incorporates knowledge of hardware and software performance in the context of the operational environment, anticipating potential problems and risks.

1.5 Remote Sensing System Development

Obviously, systems engineering is crucial and, understandably, good systems engineers are in demand. Systems engineering requires the capability 1) to integrate inputs into *the big picture* (technical breadth), focusing on, planning, overseeing, and organizing the process for the overall success of meeting mission goals (project management); 2) while harnessing the inevitable narrower focus of teams and team members (technical depth) who are responsible for subsystems and components; as well as 3) performing preliminary *back of envelope* assessments to avoid pitfalls while engaging in resourceful problem-solving when they inevitably do occur (Kossiakoff and Sweet, 2003).

The system development process (**Figure 1.8**) is no less than the application of the scientific method to engineering complex systems (Kossiakoff and Sweet 2003; International Council 1998). The problem-solving approach is recursive from step to step, and iterative within each step.

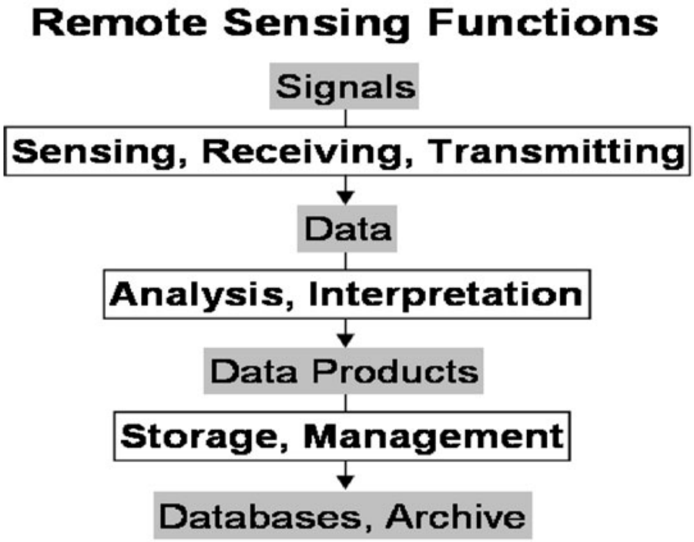

Figure 1.9 Functions and functional data elements of a Remote Sensing System

1) Requirements Analysis involves defining the problem in terms of essential inputs (goals, conditions), and required outputs (objectives, performance). The transition from rather broadly defined science goals and investigations to technical requirements and observational strategy/tactics can be challenging. The process may be facilitated early on by visualizing preliminary operational concepts or scenarios, particularly if the science tools or instruments are being used in a new way and/or humans are in the loop.
2) Functional Definition involves the *flow down* of requirements into functional components, often visualized as a block diagram or schematic. Between steps 2 and 3, various potential solutions may be considered and weighed, in terms of their impact on resources, in a process known as *trade study*.
3) Physical definition involves designing the system by envisioning functions and their interfaces in physical form, in order to build and test a working (engineering) model.
4) Design Validation and Validation involves learning how to operate and maintain the system to generate confidence that the design correctly applies all appropriate engineering rules and physical laws. Verification establishes that the system meets its requirements.
5) Production in our context means producing one or more flight models.
6) Operation and Maintenance occur during the course of the mission. Previous steps should translate into optimized performance and minimized maintenance.

From a remote sensing system standpoint, the functional components address data or signals as functional elements (Kossiakoff and Sweet 2003). Functions

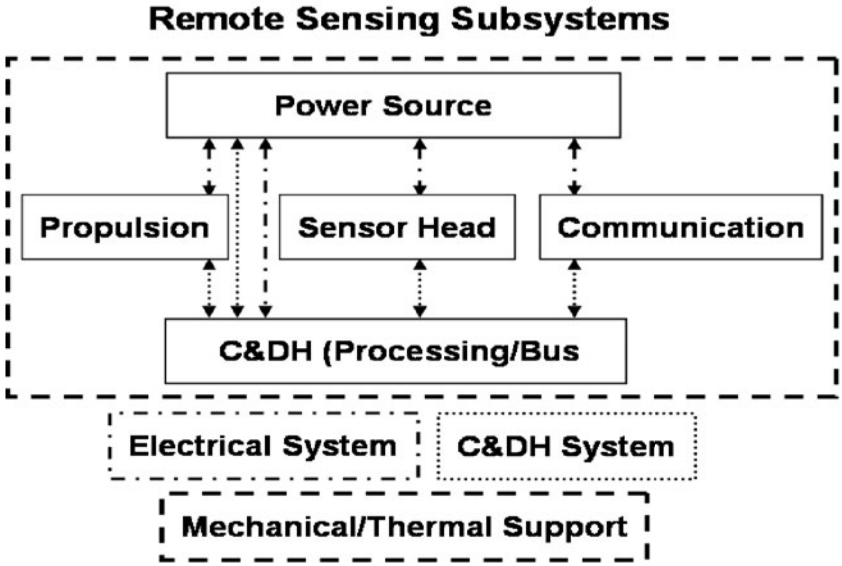

Figure 1.10 Primary Remote Sensing Spacecraft Subsystems. Electrical, C&DH, and Mechanical/Thermal Support for all of the subsystems in the spacecraft are indicated by dashed and dotted lines as shown in the key.

(**Figure 1.9**) include 1) the sensing, receiving, transmitting of signals generated from passive or active interaction of components with the environment; 2) the analysis and interpretation of data derived from signals once received, as well as 3) the storage and management of data to create datasets, databases, or archives. Essential hardware and software functional components include data storage devices for data handling, packaging material for mechanical and thermal support, mechanisms such as scanning actuators, and power components such as batteries. Functional components are contained in subsystems performing major functions (**Figure 1.10**) onboard a spacecraft. Primary subsystems include:

1) Sensor heads acquire data from various parts of the electromagnetic spectrum as described in later chapters.
2) Mechanical systems provide support and overlap with Thermal systems in providing shielding from the space environment (fields, particles, radiation, ranging from high energy space radiation to thermal radiation). Mechanisms provide actuators for closing, releasing, or actively pointing components.
3) Thermal systems maintain thermal conditions, actively or passively, to allow operation and survival of spacecraft instruments. Passive elements include insulating or conducting packaging material, radiators, and heat pipes. Active components involve dedicated heaters and coolers.
4) Power systems provide power generation (solar cells, fuel cells, radiothermal generators, chemical batteries).

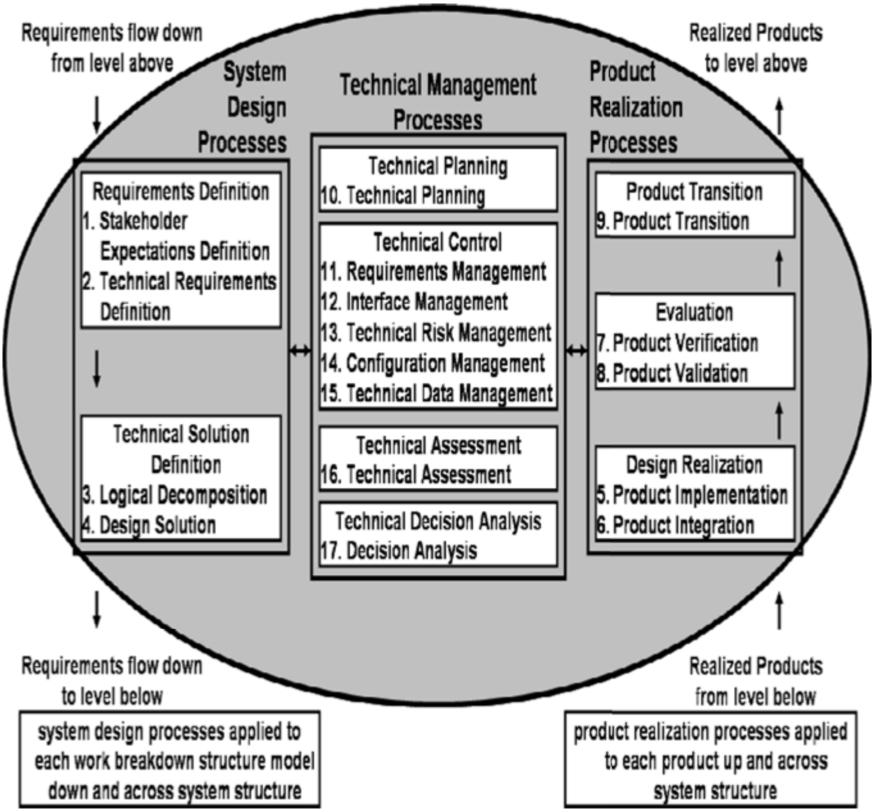

Figure 1.11 Evolutionary life cycle and Systems Engineering Model for remote sensing projects within NASA Systems Structure as discussed in the text (Courtesy of NASA).

5) Propulsion systems provide the capability for locomotion in required modes, usually one for navigation and another for maneuvering.
6) Electrical systems transmit and control power generally via a wire harness.
7) Communication, Command, and Data Handling (CC&DH) systems provide components for receiving, transmitting, processing, and storing data.

Firmware and software, as well as hardware, are included as functional components in each system in order to apply and manage its function. Interfaces play a crucial role in the system, connecting subsystems as required. The wire harness connects each subsystem to the power source. The spacecraft *bus* has I/O ports to collect and move signal through system. The power system converts voltages and provides shielding and shock protection as required.