Radio Communications for Next Generation NASA Crewed Spacecraft

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29 June 2011
Agenda

• Introduction
• (Brief) History of NASA’s Human Space Flight Program
• Spacecraft Tracking, Telemetry, and Control (TT&C)
• (Brief) History of Human Space Flight TT&C Communications
  ↘ General Dynamics Heritage
• Next Generation of NASA Human Space Flight
• Next Generation Communications System
  ↘ Next Generation Requirements for Human Space Flight
  ↘ MPCV Transponder Architecture
  ↘ Flexibility and the Software Defined Radio
• Conclusion – Q&A
U.S. Civil Space Program Timeline

1961 Mercury Freedom 7
First US man in space

1964 First Gemini Mission
APOLLO, LUNAR ORBITER, MARINER, SURVEYOR

1968-1969
VOYAGER, NASA STDN
S-BAND SPECIAL TEST EQUIPMENT, MARINER MARS

1979 STS-1
First Space Shuttle Launch
SKY LAB, PIONEER 10, MARINER 10, HELIOS
VIKING, VOYAGER I, II, PIONEER VENUS,
INTERNATIONAL SUN-EARTH, SOLAR MAXIMUM

Timeline not to scale

Images courtesy NASA and General Dynamics
U.S. Civil Space Program Timeline

1998 Russian Zarya Module
First Piece of International
Space Station Launched

2010 NASA Authorization Act:
Congress calls for NASA
to continue spacecraft development
for a Multi-Purpose Crew Vehicle
and Space Launch System
to enable crewed missions
beyond low Earth orbit by 2016


MAGELLAN, GALILEO, HUBBLE SPACE TELESCOPE, ULYSSES
SPACE STATION, NEAR, MARS GLOBAL SURVEYOR, MARS PATHFINDER, CASSINI/HUYGENS
MARS OBSERVER, CLEMENTINE, SOHO
LUNAR PROSPECTOR, DEEP SPACE I, STARDUST, MARS POLAR LANDER
IMAGE, MARS ODYSSEY, GENESIS, CONTENDER, MARS EXPRESS
MRO, JUNO, LRO, STEREO, DAWN (NEW HORIZONS), MARS LANDER


GD (Motorola) contributions

2004 Pres Bush Announces
Mission to Moon
Kicks off Constellation Program
Spacecraft TT&C

- Missiles and Spacecraft Require Fundamental Communication Capabilities
- Needs can be categorized as Telemetry, Tracking, and Control (TT&C)
  - Telemetry- Downlink spacecraft status, mission data, voice & video transmission
  - Tracking- Radiometric measurements of range (distance) and range-rate by Doppler measurement
  - Control- Uplink spacecraft configuration, navigation commands, ground voice and video
Basic TT&C Systems -
Early launches used 3 separate systems

- Early uncrewed and crewed launches including Mercury and Gemini used separate systems and radio spectrum for each function
  - Radar systems used for tracking
  - Low frequency VHF or UHF used for control, voice and telemetry

Early Launches included separate radar tracking, telemetry and command transmission systems

C-Band Radar Tracking
Range, Position, Range Rate

VHF/UHF Voice, Commands

VHF/UHF Voice, Telemetry
Basic TT&C Systems- “Unified” S-Band

- Apollo Mission to the Moon Created Unique TT&C Needs
  - Lunar insertion, trans-lunar flight, LEM separation, landing and docking require accurate tracking at extreme distances
  - Multiple space vehicles operating simultaneously
  - More critical re-entry phase requires accurate tracking
  - Additional command and telemetry data capacity needed, including television/video

- Unified S-Band System Developed for Apollo
  - Combines Tracking, Telemetry, and Control into one system
    - Added capability for voice and television, emergency comm.
  - One spectrum and one spacecraft radio handles all 3 functions along with voice and television
  - Capable of long distance tracking using radio PN code, range rate using carrier Doppler shift measurement
Basic TT&C Systems – Unified S-Band Developed for Apollo

Figure 1. Apollo Unified S-Band System Capabilities

S-Band Return Link
Telemetry, Data, Spacecraft Voice

S-Band Forward Link
Command/Control
Ground Voice

Unified S-Band and
Ground Network TTC

Unified S-Band combined
TT&C functions into one
radio “Transponder”

Figures taken from NASA Document TM X-55492, April 1966
Basic TT&C Systems - Unified S-Band Transponder and Spectrum

Figure 9. Basic Spacecraft System for Command Module

Figure 8. Uplink Spectrum

Figures taken from NASA Document TM X-55492, April 1966
Basic TT&C--
Tracking & Data Relay Satellite System

- Limitations of Unified S-Band and Shuttle Development Drove Need for Better TT&C capability
  - USB system required 11 ground stations for near-earth TT&C
  - Full orbital coverage not available
  - Limited user and data-rate capacity

- The Tracking and Data Relay Satellite System (TDRSS) system began development in the mid 1970’s
  - TDRSS design was based on ground station USB TTC system previously used

- TDRSS is a system of geosynchronous satellites implementing the TT&C functions
  - User satellites communicate with a TDRSS satellite using S-Band or Ku-Band crosslinks with full orbital coverage
  - TDRSS satellite translates user signals to/from Ku-Band and link to TDRSS ground stations.
  - Ranging and Range-rate tracking is accomplished relative to the TDRSS satellite position.
TDRSS System Operation

- Services to White Sands Ground Terminal Shown
  - Guam Ground Terminal Operation is Similar
Basic TT&C
TDRSS Communications

- The TDRSS system uses direct sequence spread spectrum
  - Leverages the need for PN-code ranging capability to include advantages of spread spectrum systems
  - One of the first space applications of spread spectrum
  - ~3 Megachip direct sequence spreading

- Advantages of Spread Spectrum
  - Many users share the same frequency by assigning each a unique PN code. This is known as “code division multiple access” (CDMA). Now utilized in cell phones and wireless systems
  - Transmitted power is spread over a wider portion of the frequency spectrum reducing interference to other users
  - Interfering signals, including multi-path, are rejected as they are scrambled by the receiver’s PN code
  - The PN code time delay is also used to measure the distance from the ground station to the satellite for tracking purposes.

- Multiple Access and numerous Frequency bands Provide high user communications capacity
Basic TT&C Ranging and DS Spread Spectrum

- Direct Sequence Spread Spectrum comes virtually for free with PN Ranging capability

![Diagram showing basic TT&C ranging and DS Spread Spectrum](image-url)
Tracking and Data Relay Satellite System (TDRSS)

- 10 satellites in service, including parked spares
- Ground Stations in White Sands, NM, and Guam
- 2 Generations currently flying, 3rd generation in production
- Newer generations add wide-band Ka-Band capability on crosslinks
U.S. Crewed Missions TTC & Comm.

- Project Mercury, Project Gemini
  - UHF/VHF main voice communications
  - UHF Command Receiver for commands and voice backup
  - C-Band Radar Transponder for tracking
- Apollo
  - Unified S-Band 2-way Radio Transponders for comm. and tracking
    - Command Module (2) & Lunar Module
  - Lunar Rover FM Voice/Command receiver
  - Command/Destruct receivers on booster stages 1, 2, 3
- Space Shuttle
  - Unified S-Band and TDRSS Transponder Capability (Not GD/Motorola)
- Space Station
  - Motorola/General Dynamics S-Band TDRSS/STDN Transponder
General Dynamics Scottsdale Heritage

- Originally Motorola’s Military/Government Electronics Group
  - Established in late 1940’s in Phoenix area
  - Expanded into Scottsdale facility in mid 1950s
- Space communications grew out of missile electronics developed in mid-1950s
  - Need emerges for vehicle Tracking, Telemetry, and Control by ground stations
  - Motorola was a leading supplier of missile command/destruct receivers
- Project Mercury begins in 1958
  - Motorola MCR-100 series UHF receiver used for reliable backup communications
  - Flew on all Mercury missions
  - 10 channel Uplink commands plus voice backup
    - Relay control outputs
  - Mercury utilized worldwide radar tracking system

Figure taken from Motorola Datasheet
General Dynamics Scottsdale Heritage

- Project Gemini and Agena Docking Vehicle Components
  - Motorola C-Band Radar Transponder for Tracking range, position and velocity
    - Gemini utilized worldwide radar ground-based tracking system
  - Motorola Digital Command System, UHF command receiver for Gemini
    - UHF FM modulation with PSK modulated sidebands and relay control outputs
    - Similar Motorola Digital Command System for Agena docking vehicle

Figure taken from Motorola Datasheet
General Dynamics Scottsdale Heritage

- Project Apollo Mission Components from Motorola/GD
  - Unified S-Band Transponder, Command Module (CM)
  - Unified S-Band Transponder, Lunar Module (LEM)
  - S-Band Communications transponder, 3\textsuperscript{rd} Stage
  - Lunar Rover FM Command/Voice Receiver
  - Up-Data Link unit, (Data handling) Command Module
  - Flight Data/Command Destruct Receivers Stages 1,2,3
  - S-Band Command Receiver, ALSEP Experiment

Images courtesy NASA and General Dynamics
General Dynamics Scottsdale Heritage

- Project Apollo Mission GDAIS/Motorola Components “on the rocks”
General Dynamics Scottsdale Heritage

- Space Station Freedom/ISS Mission Components
  - HRFM (High Rate Frame Mux; 2 units, part of the K-band system)
  - HRM (High Rate Modem; 2 units, part of the K-band system)
  - ACBSP (Assembly Contingent Baseband Signal Processor; 3 units, part of the S-band system)
  - XPDR (TDRSS Transponder; 3 units, part of the S-band system)

Images courtesy NASA and General Dynamics
TTC Spacecraft Transponder Basics

- USB/First Generation TTC Transponder Block Diagram

[Diagram showing signal flow through transponder components: XM, DEMOD, COHERENCY SELECT, MODULATOR CARRIER REFERENCE, TELEMETRY DATA FOR DOWNLINK, RECOVERED CONTROL DATA, RECOVERED RANGE, RECOVERED CARRIER, REFERENCE SOURCE.]
TTC Spacecraft Transponder Basics

- TDRSS Spread Spectrum TTC Transponder Simplified Block Diagram

Diagram with blocks and labels:
- Reference Source
- XN
- XM
- PD
- Downlink Code Gen
- Code Ref
- SP Spectrum Code Tracking
- COHERENCY SELECT
- MOD
- MODULATOR CARRIER REFERENCE
- Telemetry Data for Downlink
- Recovered Range Code
- Recovered Control Data
- Recovered Carrier
Next Generation US Human Space Flight Program

- In 2004, President Bush challenged NASA to send the U.S. back to the Moon and Mars
  - Kicked off ambitious Constellation Program to redefine the U.S. human space flight program
    - Replaces the aging Space Shuttle system including following segments:
      - Ares Heavy Lift Booster development,
      - Orion Crew Exploration Vehicle (CEV)
      - Altair Lunar Excursion vehicles

Images Courtesy NASA
Ongoing Changes to U.S. Human Space Flight Program

- Obama Administration in 2010 Directed Changes to NASA’s Human Space Flight Program Objectives
  - Constellation and Orion Programs Cancelled
  - Lengthened schedule for return to the Moon, focuses on Shuttle replacement in near term
  - Increased Private Sector Involvement to develop space vehicles
- 2010 NASA Authorization Act Redirects NASA goals:
  - Continue development of Multi-Purpose Crew Vehicle (MPCV) and Space Launch System to enable crewed missions beyond low Earth orbit by 2016
    - MPCV based on Orion CEV baseline
  - Evolutionary approach and architecture supports changing objectives and timeframes
TTC and Communications for Human Space Flight Operations

- Tracking and Communications System for human space flight must support present and future missions
  - Immediate need for missions to ISS space station, including launch, rendezvous/docking, return to earth—Shuttle Replacement
- Future missions could include Lunar orbit, asteroid missions, Mars excursions and beyond
  - Near earth operations: launch support, early Earth-orbit operations, rendezvous, in space operations, lunar transit, re-entry and landing operations
  - Lunar Operations: orbit insertion, observation, scientific surveys, and Earth transit
  - Mars Operations: Mars transit, Mars orbit insertion, surface operations, ascent, and Earth transit
- Long reaching plans dictate need for evolutionary approach to TTC infrastructure
TTC and Communications for MPCV

- TTC requirements for the Multi-Purpose Crew Vehicle (MPCV) focus on immediate needs with long range mission requirements in mind
  - Near Earth needs will be satisfied by the existing Space Network Tracking and Data Relay Satellite System (TDRSS) constellation through 2025
    - Planned TDRSS upgrade deployment occurs in the 2015 time frame
  - Space-to-space TDRSS TTC allows docking and communications directly between MPCV and ISS or MPCV and Moon missions.
    - Requires dual-mode transponder capable of operation in a space-based user transponder mode or operation in Earth station mode.
      - Capabilities include space-borne ranging and range-rate measurement
  - Similar to Apollo, initial lunar sortie missions will be supported by Earth ground stations, primarily the Deep Space Network (DSN)
    - DSN upgrades planned for TDRSS compatible receivers supporting MPCV
TTC and Communications for MPCV Support
Evolution of Human Space Flight Program
MPCV POINT A/B S-BAND TRANSPONDER

RECEIVED S-BAND

TRANSMIT S-BAND

RECOVERED UPLINK & COMMAND DATA

TRANSPONDER CONTROL/STATUS DATA BUS

TELEMETRY & DOWNLINK DATA

FPGA SIGNAL PROCESSING, TDRSS WAVEFORMS

INCLUDES COHERENT RX/TX TURNAROUND

ADC

PROM

SRAM

COLDFIRE uP

PLL SYNTHESIZER

XM, Pt A

XN, Pt B

PLL SYNTHESIZER

XM, Pt B

XN, Pt A

TCXO

DAC

SIGNAL PROCESSING, TDRSS WAVEFORMS

INCLUDES COHERENT RX/TX TURNAROUND

TELEMETRY & DOWNLINK DATA

GENERAL DYNAMICS
Advanced Information Systems
MPCV S-BAND TRANSPONDER OVERVIEW

- Functional Overview
  - TDRSS Waveform Compatible
  - Point A (User Transponder) or Point B (Ground Station Mode) Operation
  - Operation on 3 TDRSS frequency bands
  - Capable of majority of TDRSS waveforms on command
  - Coherent or non-coherent operation
  - Waveforms instantiated in Software and FPGA Gateware
  - Radiation hardened and ruggedized for operation during launch
  - New bandwidth efficient modulation waveforms (non-spread)
    - better spectrum utilization and higher bit rates
    - Root-Raised Cosine pulse shaping
MPCV S-BAND TRANSPONDER OVERVIEW

- Physical Characteristics
  - Mass: 10 lbs
  - DC Power: 19 W, Tx & Rx
MPCV S-Band Transponder is STRS Compatible

- Our MPCV Transponder utilizes NASA’s Space Telecommunications Radio System (STRS) Software Defined Radio (SDR) architecture
  - Developed for CONNECT program
  - High level operating system provides standardized open-architecture approach
  - STRS Outer Layer provides seamless interface to detailed waveform and hardware functions
  - SDR Minimizes need for costly hardware changes
- Allows use of STRS Repository
  - Collection of hardware and software modules, definitions, documents for mission reuse
  - Allows for 3rd Party developers to easily update radio function
- Result is increased capability for evolution with changes in human space program objectives.
SDR/STRE Conceptual Diagram

General Processing Module (GPM)
- Ground Test Interface
- Host/T&TC Interface
- Work Area Memory
- Persistent Memory
- General Purpose Processor
  - Waveform / Application
  - Operating Environment
  - Low Speed Signal Processing
  - Radio Configuration & System Control

Signal Processing Module (SPM)
- Test & Status
- System Control
- Clock Distribution
- Spacecraft Data Interface
- Data Buffer / Storage
- Data Formatting
- High Speed Digital Signal Processing
  - Waveform

RF Module (RFM)
- Variable Gain / Frequency
- Clock Interface
- Antenna Control Interface
- Test & Status
- Receive RF
  - Analog to Digital
  - Digital to Analog
- Transmit RF
  - Analog to Digital
  - Digital to Analog
  - Test & Status

Advanced Information Systems
STRS Software Architecture

[Diagram of STRS Software Architecture showing relationships between components and subsystems, including STRS Radio, RTOS, STRS CE, STRS Infrastructure, HIL, Specialized Hardware, and various APIs and interfaces.]
Summary and Conclusions

- General Dynamics AIS Scottsdale has a long heritage supporting the U.S. Human Space Flight Program
  - We are pleased to support NASA and the world in continuing human exploration of space
- Our MPCV S-Band Transponder Supports NASA’s need for an Evolutionary TTC System
  - Supports near term needs but provides flexibility for the future
  - Flexibility provided by Software Programmable architecture
  - Capability of operation in TDRSS Point A or Point B Modes
- STRS SDR Provides for easy update of the MPCV transponder function to meet the needs of the future of Human Space Flight
Q&A

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Motorola’s Government Electronics Group was acquired by General Dynamics in 2001.