Bandwidth-Efficient Communication through 225 MHz Ka-band Relay Satellite Channel

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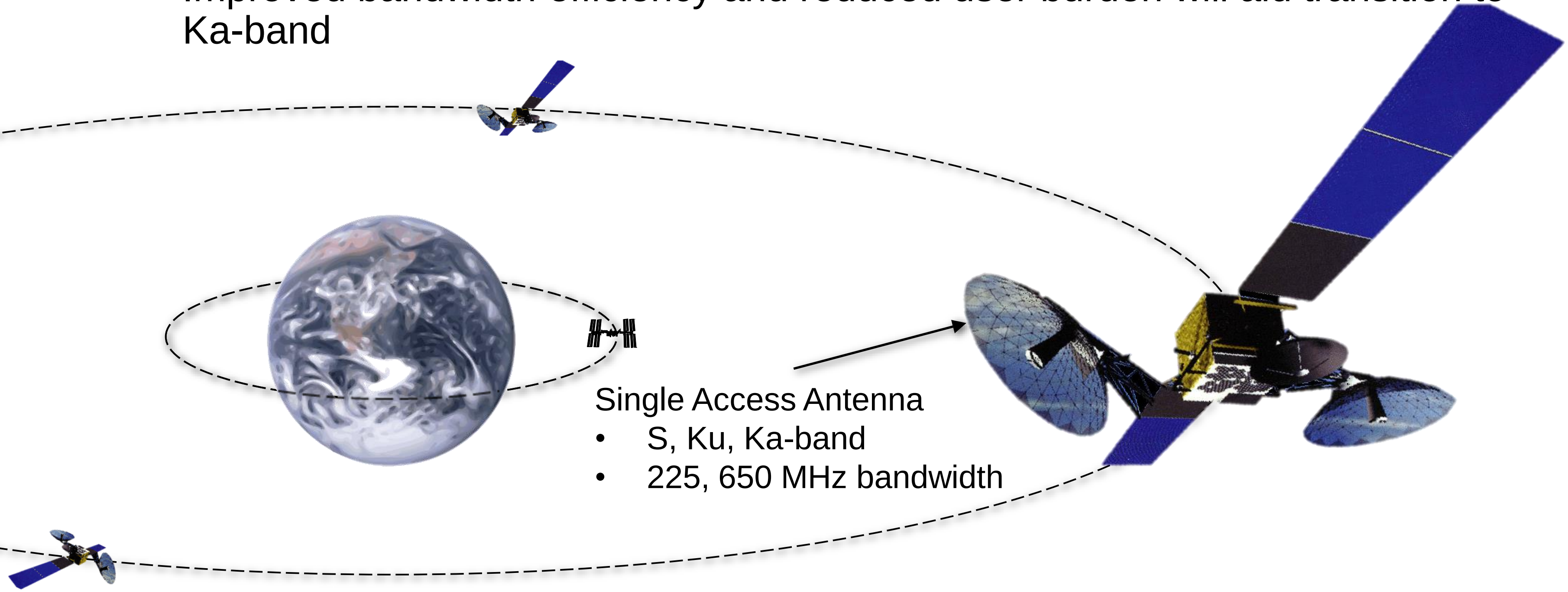
Outline

- Current and Future NASA Communication Architecture
- High-rate Flight Experiment through Ka-band Relay
- Test Results
- Conclusions

NASA’s Near Earth Relay Satellite System

- NASA’s Tracking and Data Relay Satellite System (TDRSS) has multiple communication relay satellites in geostationary orbits, and provides continuous coverage to low-Earth orbiting spacecraft
  - Ku-band and Ka-band provide wideband (225/650 MHz), high data-rate channel for science data return
- NASA’s use of Ka-band through relay satellites and direct-to-ground is expected to increase significantly in coming years
- Improved bandwidth efficiency and reduced user burden will aid transition to Ka-band



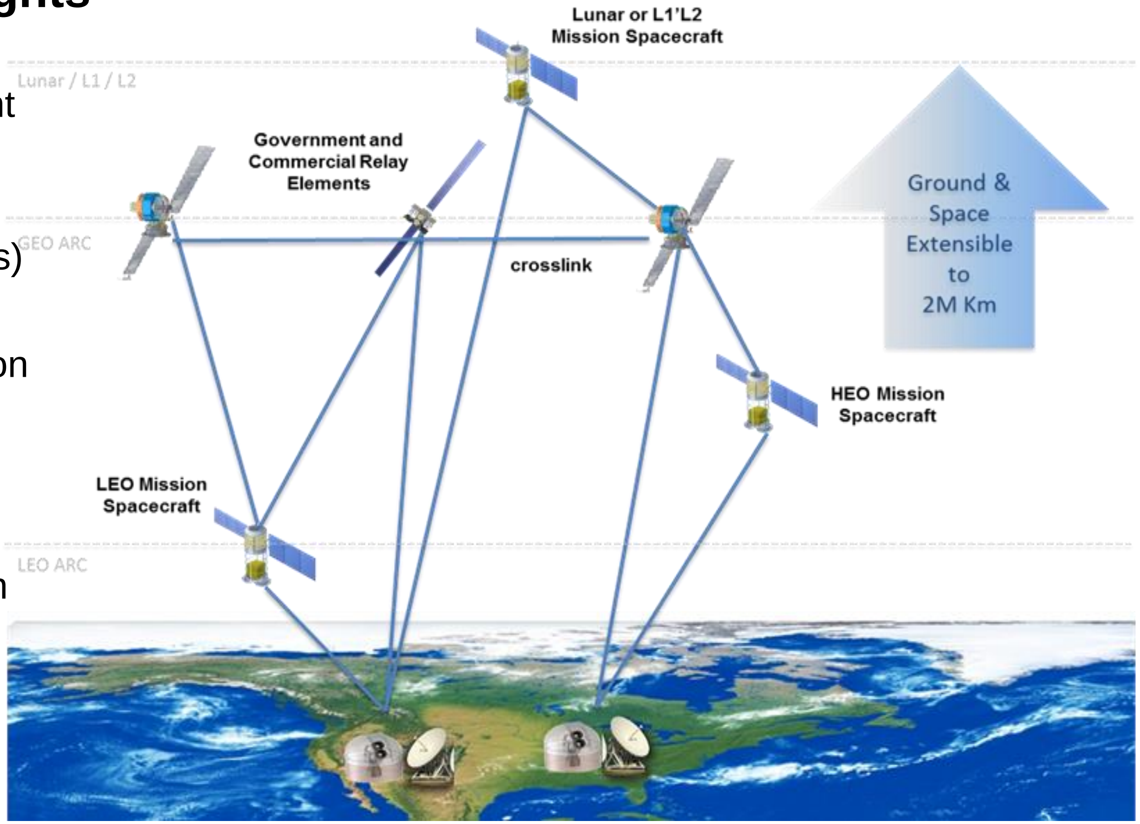
Single Access Antenna

- S, Ku, Ka-band
- 225, 650 MHz bandwidth

Next Generation Near-Earth Network Concept

- **New/Enhanced Services Highlights**
  - Increased data rate (> Gbps)
  - Improved networking (IPv6 & delay tolerant networking (DTN)
  - On-demand, flexible service
  - Messaging/control service (multiple access)
  - Cognitive communications
  - Inter-agency service management based on CCSDS standards

- **Earth Network Architecture**
  - Full coverage network with relay orbiters in GEO & possibly other orbits
  - Mix of NASA, commercial, & international service providers
  - Ground/space assets for low end-to-end forward/return data latency
  - Optical ground telescopes provide continuous optical support



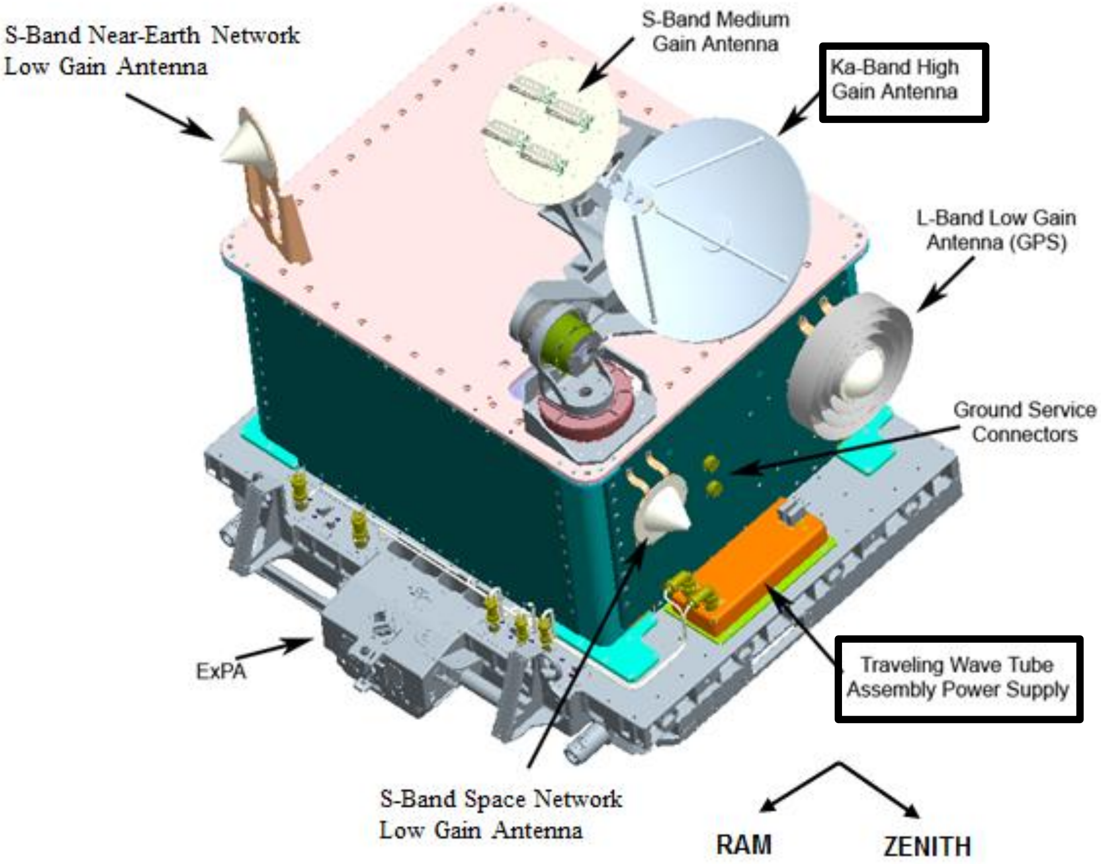
Notional Earth Architecture

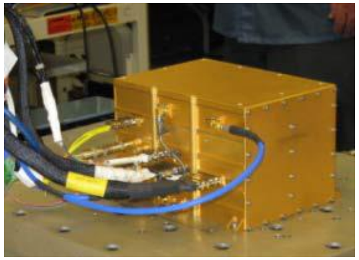
Flight Experiment Objectives and Goals

- Maximize throughput over the 225 MHz Ka-band relay channel using bandwidth-efficient techniques
- Develop methods to compensate for gain and phase distortions over the bandlimited channel, including non-linear distortions from travelling wave tube (TWT) amplifiers

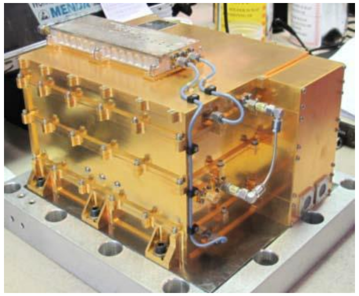
	Modulation	Code Rate	Data rate through 225 MHz (Mbps)
Current practice	OQPSK, Low-pass Filtered	1/2 7/8	100 262
Experiment goal	Precoded GMSK, (BT=0.3)	7/8	175
	OQPSK, (SRRC 0.2)	7/8	350
	8-PSK, (SRRC 0.2)	7/8	525
	16-APSK, (SRRC 0.2)	7/8	700
	32-APSK, (SRRC 0.2)	7/8	875

Space Communication and Navigation Testbed on the International Space Station





General Dynamics SDR
S-band Transceiver
(1) Virtex-2 FPGA
8W amp



JPL / L3-CE SDR
S-band Transceiver,
L-band (GPS)
(2) Virtex-2 FPGAs
7W amp

Harris Corporation SDR
Ka-band Transceiver
(4) Virtex 4 FPGAs, DSP
40W TWTA

Link Budget

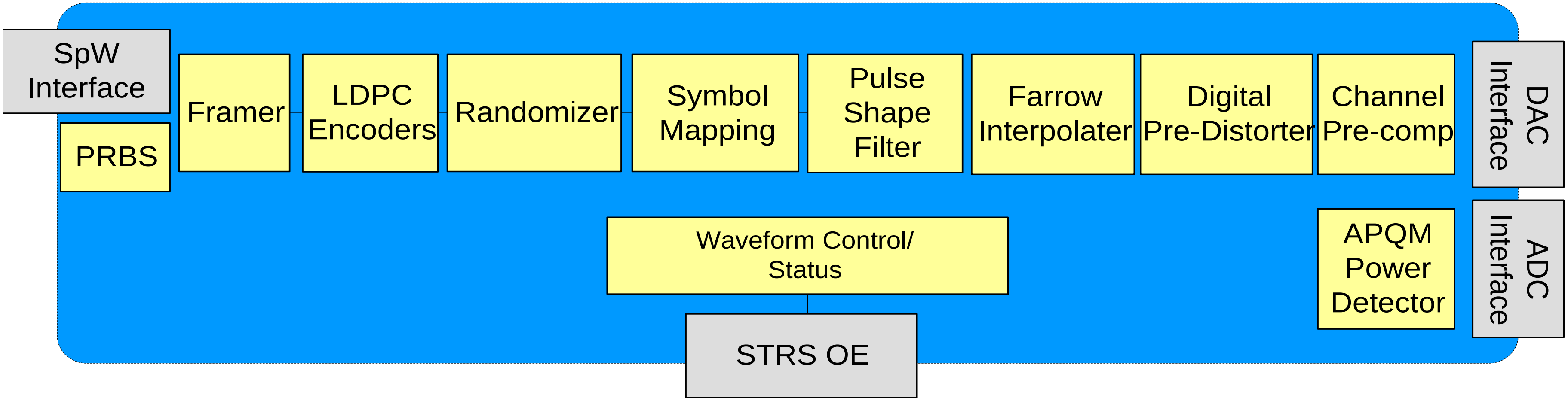
SCaN Testbed - Ka-band Sub-System

- Gimbaled, 46 cm Parabolic Dish Antenna
- Closed-loop tracking via received signal strength
- Traveling Wave Tube Amplifier (40W, 45% efficiency)

Parameter	Value
Frequency (GHz)	25.65
EIRP (dBW)	52.75
Channel Loss (dB)	212.59
Received Isotropic Power (dBW)	-159.84
TDRS G/T specification (dB/K)	23
Boltzmann's Constant (dBW/K/Hz)	-228.6
TDRS Ku-band Downlink C/N_0 (dB-Hz)	110.5
C/N_0 at Ground Station (dB-Hz)	91.71*

*Operational testing with SCaN Testbed has observed C/N_0 up to 99 dB-Hz, due to higher actual TDRS G/T

High-rate Bandwidth-Efficient Transmitter



Modulation: GMSK, BPSK, OQPSK, 4/8/16-PSK, 16-QAM, 16/32-APSK

Data Rate: Adjustable, 1000 Mbps

Pulse-shape Filtering: 128-taps, SRRC and RC, various roll-offs

Forward Error Correction: LDPC, AR4JA ½, 2/3, 4/5, C2 rate 7/8

Framing: CCSDS Framing and Randomizer

Digital Pre-distortion: Memory-less, Symbol Pre-distortion

Channel Pre-compensation: 32-tap FIR

Waveform is available via STRS Repository: https://strs.grc.nasa.gov/

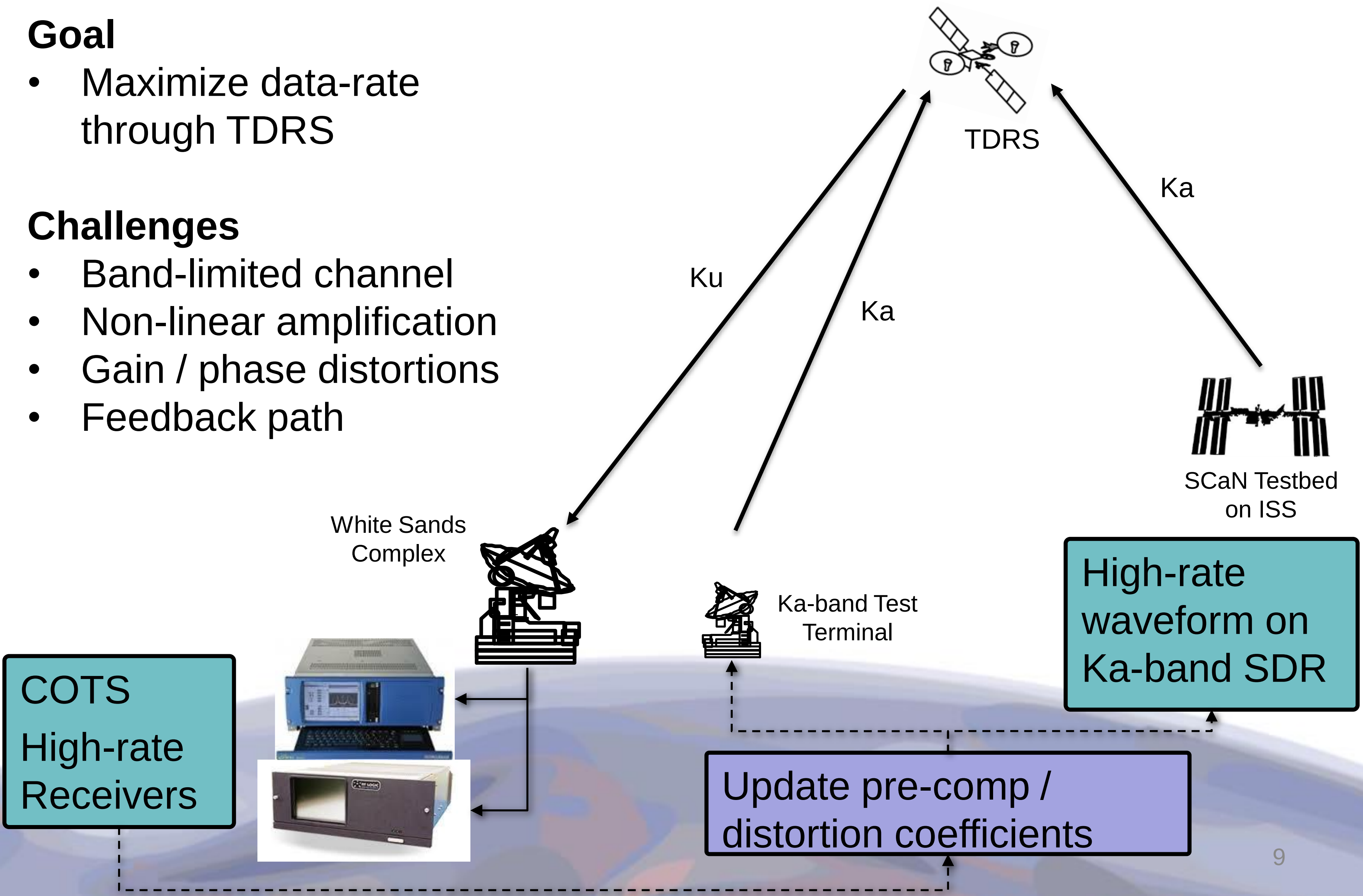
Experiment Test Configuration

Goal

- Maximize data-rate through TDRS

Challenges

- Band-limited channel
- Non-linear amplification
- Gain / phase distortions
- Feedback path



High-rate waveform on Ka-band SDR

COTS

High-rate Receivers

Update pre-comp / distortion coefficients

Results Summary

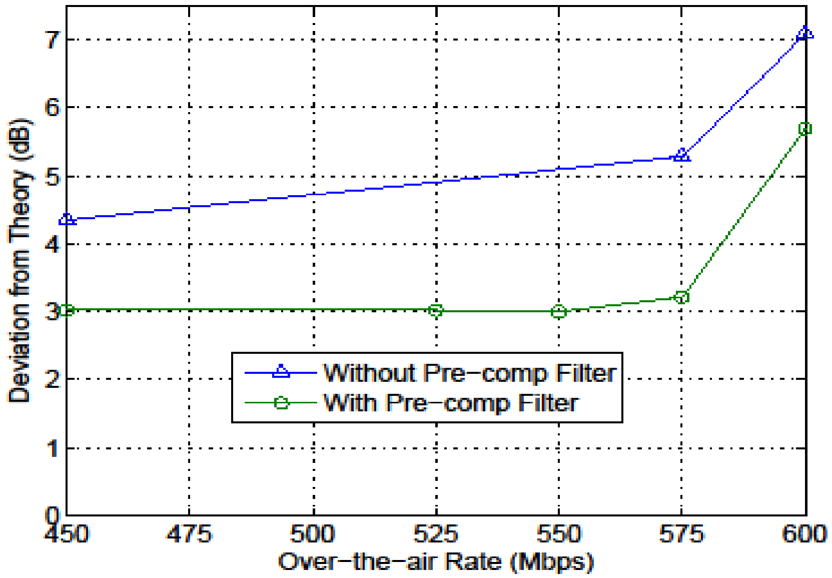
- Ka-band Test Terminal enabled near 700 Mbps over the 225 MHz channel, band limiting distortions limited full potential
- SCaN Testbed achieved 400-500 Mbps with 8-PSK, LDPC 7/8, power and bandwidth limited
  - Performance varied between TDRS satellites (2nd vs. 3rd generation) and dedicated versus composite signal configuration

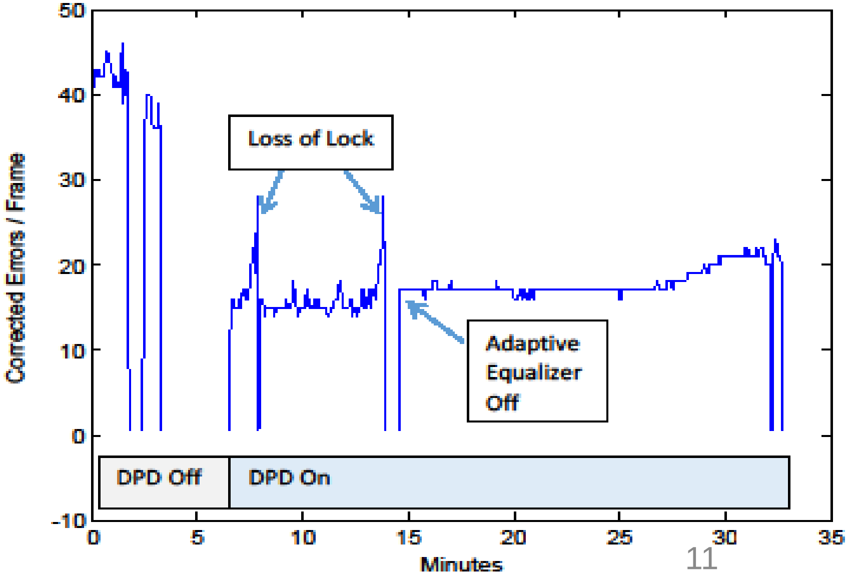
Modulation	Filter	Encoding	Ka-band Test Terminal	SCaN Testbed on ISS
GMSK	Gaussian, BT=0.3	Uncoded	200 Mbps*	
OQPSK	SRRC 0.2	LDPC 7/8	350 Mbps*	
8-PSK	SRRC 0.2	LDPC 7/8	525 Mbps (1e-10)	525 Mbps (1e-5)
16-APSK	SRRC 0.35	LDPC 7/8 LDPC 2/3	678 Mbps (1e-9) N/A	262.5 Mbps (1e-10) 433.3 Mbps (1e-8)

* Bit-error rate: 1e-12

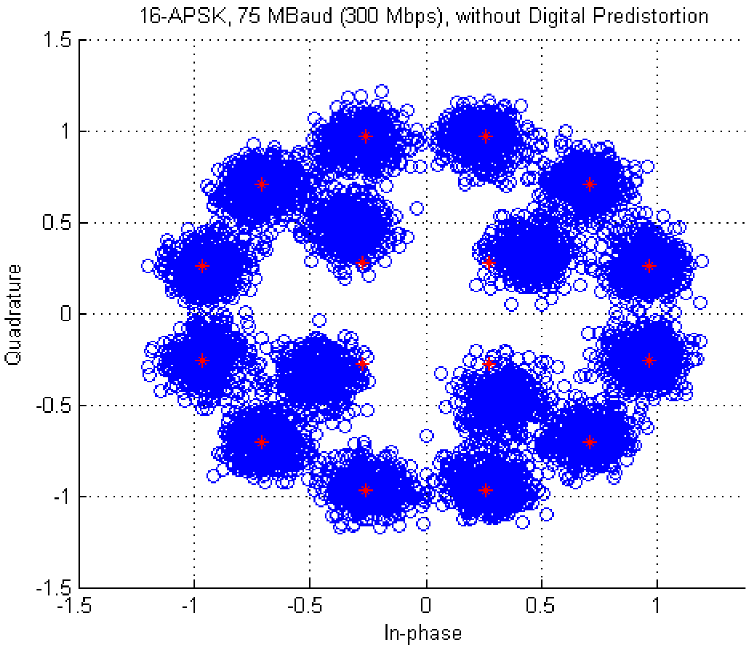
Challenges due to bandlimited channel

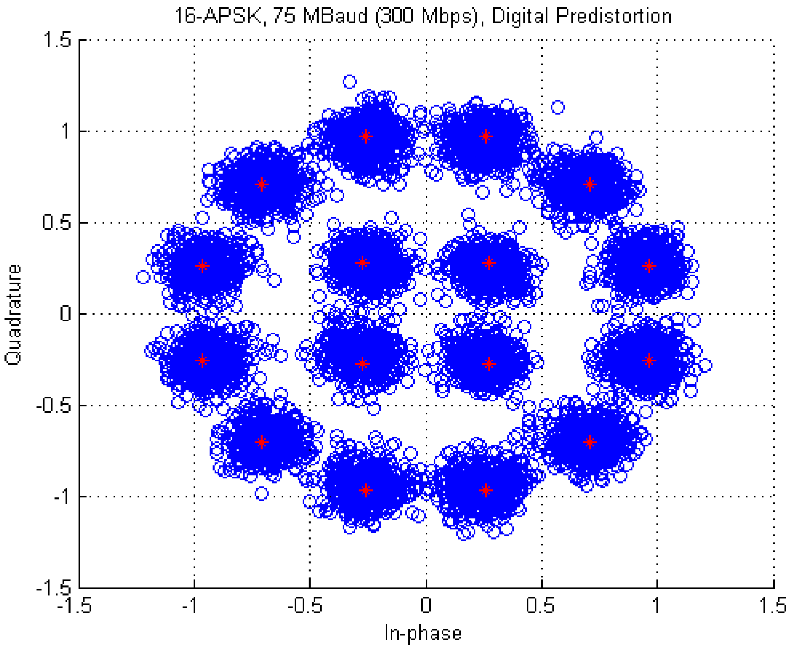
- Substantial system loss as bandwidth increases.
  - Receiver adaptive equalizer not sufficient, pre-compensation required at transmitter
- Highest symbol rates were problematic for adaptive equalizers to track – better performance with custom filter matched to channel
  - Potential issue for operations at these bandlimited conditions – spacecraft may need to re-train matched filters on ground receiver throughout mission





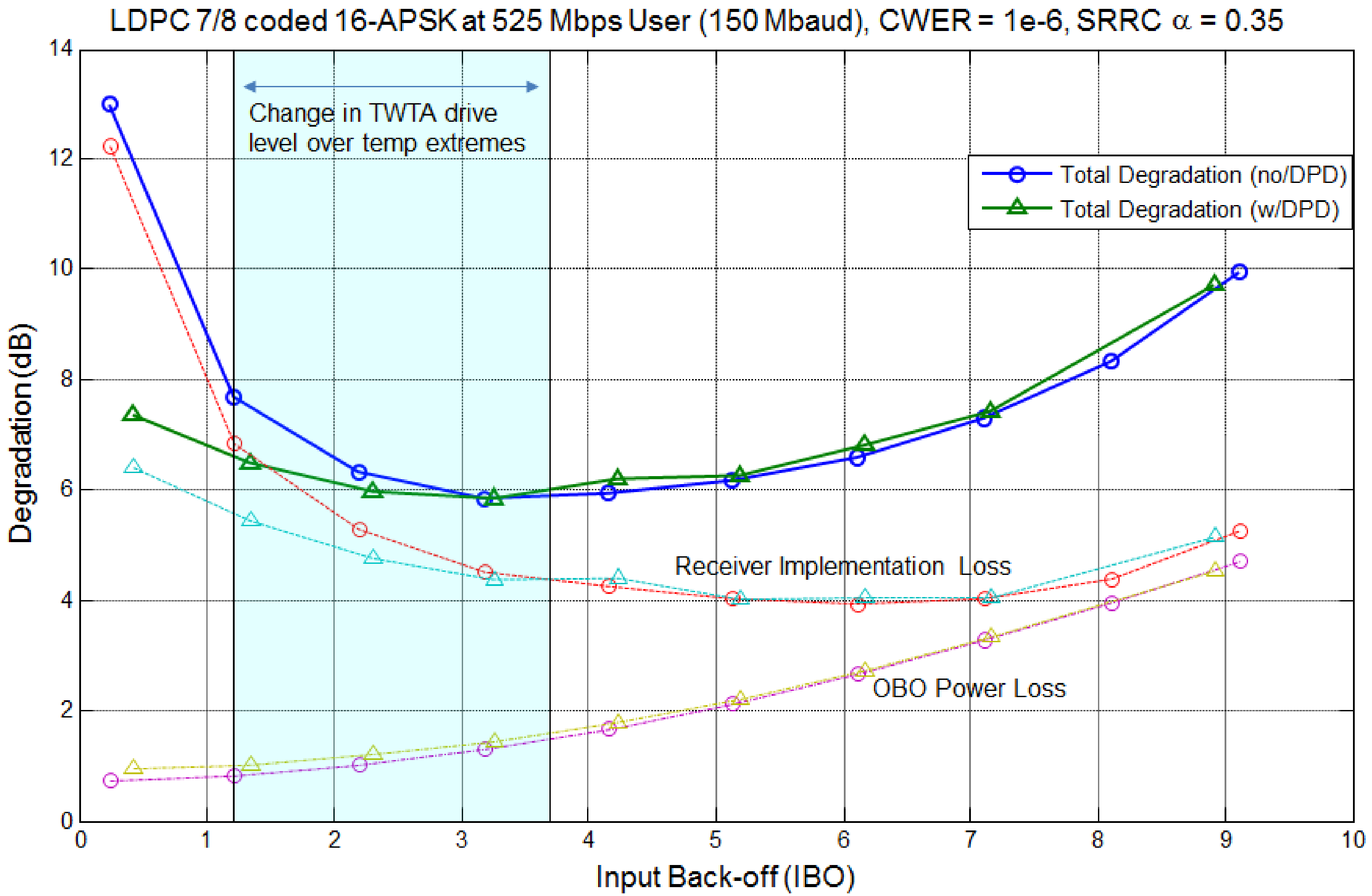
Non-linear Digital Pre-distortion


16-APSK, 75 MBaud (300 Mbps), without Digital Predistortion


16-APSK, 75 MBaud (300 Mbps), Digital Predistortion

- Primary source of non-linear distortion is the user space-craft power amplifier (e.g. TWTA)
- Static symbol predistortion (adjusting amplitude ratio and the relative phase between the inner and outer rings)
- In-situ channel characterization – use measurements at ground receiver to automate channel correction

TWTA Optimal Drive Level



- Pre-distortion provided minimal gain 0-0.25 dB, depending on code rate
- Static pre-distortion was effective in improving performance and stability, especially near saturation point of amplifier

Summary and Conclusions

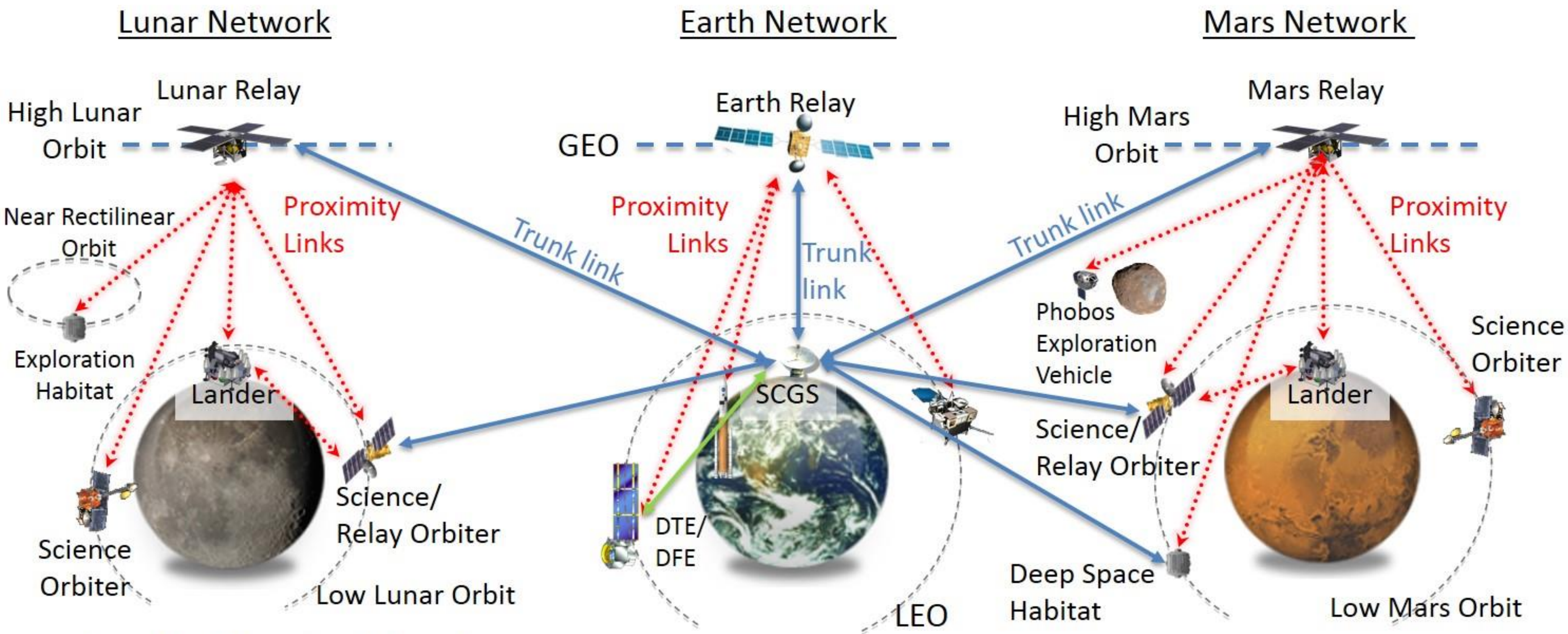
- Demonstrated reconfigurable bandwidth-efficient waveforms
- Validated user data rates 700 Mbps over the 225 MHz channel, with 500 Mbps from space flight radio
- Demonstrated digital pre-distortion and pre-compensation techniques as companions for higher-order modulations
- Modulation waveform code in STRS repository for re-use

Backup

Next Generation SCaN Architecture Vision

- “Shrink” the solar system by connecting the principle investigator more closely to the instrument, the mission controller to the spacecraft, and the astronaut to the public
- Improve the *mission’s experience* and reduce *mission burden* – the effort and cost to design/operate spacecraft to receive services from SCaN Network
- Reduce *network burden* – the effort and cost required to design, operate, and sustain the SCaN Network as it provides services to missions
- Apply new and enhanced capabilities of terrestrial telecommunications and navigation to space, leveraging other organizations’ investments
- Enable growth of commercial services for missions currently dominated by government capabilities
- Enable greater international collaboration and lower costs in space by establishing an open architecture with interoperable services that can be adopted by international agencies and as well as NASA

Planetary Networks:
Earth, Moon & Mars – One Architecture



Benefits of Planetary Networks:

- Reduced mission burden with short links for in-system communications - enables in-system telerobotics
- Common architecture reduces technology & development costs
- Reuse of HW & SW: Family of products includes variants for different environments
- Reuse of spectrum

Architect for Flexibility, Scalability, & Affordability –
Implement as required to meet specific mission needs