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"DEEP SPACE COMMUNICATIONS, WEATHER EFFECTS, AND ERROR CONTROL"

Edward C. Posner
Jet Propulsion Laboratory

ABSTRACT

Deep space telemetry is and will remain signal-to-noise limited and vulnerable to interference. We do all we can to increase received signal power and decrease noise. This includes going to Ka-band (32 GHz down) in the mid-1990's to increase directivity. This is in spite of the increased difficulty of maintaining surface accuracy, pointing the spacecraft and ground antennas, and accommodating to weather uncertainty. The effects of a wet atmosphere can increase the noise temperature by a factor of 5 or more, even at X-band (8.5GHz down), but the order of magnitude increase in average data rate obtainable at Ka-band relative to X-band makes the increased uncertainty a good trade. The 32GHz frequency is likely to be the highest frequency used operationally from deep space in the next 15 to 20 years. Lowbit error probabilities required by data compression are available both theoretically and practically with coding, at an infinitesimal power penalty (.05-.2dB) rather than the 10-15dB more power required to reduce error probabilities without coding. Advances are coming rapidly in coding, as with the new constraint-length 15 rate 1/4 convolutional code concatenated with the already existing Reed-Solomon code to be demonstrated on Galileo. These advances will get NASA ready for the day when high-compression-ratio telemetry will require 10^{-6} to 10^{-9} bit error probability. In addition, high density spacecraft data storage will allow selective retransmissions, even from the edge of the Solar System, to overcome weather effects. In general, deep space communication has been able to operate, and will continue to operate, closer to theoretical limits than any other form of communication. These include limits in antenna area and directivity, system noise temperature, coding efficiency, and

everything else. The deep space communication links of the mid-90's and beyond will be compatible with new instruments and compression algorithms and represent a sensible investment in an overall end-to-end information system design.

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BY EDWARD C. POSNER

TELECOMMUNICATIONS AND DATA ACQUISITION OFFICE
JET PROPULSION LABORATORY

PRESENTED AT NASA SCIENTIFIC DATA COMPRESSION WORKSHOP
SNOWBIRD, UTAH

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OUTLINE

- UNIQUENESS OF DEEP SPACE COMMUNICATION
- NOISE AS A LIMITING FACTOR
- FREQUENCY SELECTION
- WEATHER EFFECTS
- CHANNEL CODING AND DATA COMPRESSION
- VISIBLE FUTURE TELEMETRY TRENDS
- SUMMARY

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UNIQUENESS OF DEEP SPACE COMMUNICATIONS

- WEAK SIGNALS
  - SIGNALS FROM EDGE OF SOLAR SYSTEM TO EARTH SUFFER MORE THAN 10 BILLION TIMES AS MUCH PATH LOSS AS THOSE FROM SYNCHRONOUS ORBIT
  - IMPLIES CONSERVING SIGNAL POWER MORE IMPORTANT THAN OTHER CONSTRAINTS, E.G., BANDWITH
  - MAKES DEEP SPACE SIGNALS MORE VULNERABLE TO INTERFERENCE
- LONG PROPAGATION TIMES
  - ONE-WAY TIME FROM EDGE OF SOLAR SYSTEM 4 HOURS INSTEAD OF 0.1 SEC FROM SYNCHRONOUS ORBIT
  - IMPLIES ONE-WAY BULK DATA TRANSMISSION APPROPRIATE WITH LITTLE USE OF FEEDBACK
  - MAKES IT HARD TO ADJUST SPACECRAFT BASED ON CONDITIONS AT EARTH

NOISE AS A LIMITING FACTOR

- CHANNEL CAPACITY DETERMINED BY RECEIVED SIGNAL POWER, NOISE POWER, AND (LESS IMPORTANT FOR DEEP SPACE) BANDWIDTH
- NOISE POWER IS RECEIVED FROM
  - COSMIC BACKGROUND
  - PLANET IN BEAM, ESP. VENUS
  - EARTH's ATMOSPHERE (WET IS WORSE)
  - EARTH ITSELF (SIDELOBES, BACKLOBES)
  - RECEIVER FRONT END
- NOISE POWER SPECTRUM TENDS TO BE FLAT (WHITE) ACROSS BAND, OF HEIGHT OR POWER SPECTRAL DENSITY $N_0 = kT$
  - k IS BOLTZMAN'S CONSTANT, T IS SYSTEM TEMPERATURE IN KELVINS
- CHANNEL CAPACITY C IN BITS/SEC IS THEN
  - $C = P_R / N_0 \ln 2$ (P_R IS POWER RECEIVED)

CONTROLLING NOISE

- 3 K COSMIC BACKGROUND AND PLANET IN BEAM ARE NOT CONTROLLABLE NOISE SOURCES
- EARTH's WET ATMOSPHERE DEVASTATING BECAUSE SIGNAL ABSORBTION EQUIVALENT TO NOISE RADIATION
  - EXAMPLE: 10% ABSORPTION SEEMS MINOR (0.46 dB LOSS), BUT IMPLIES 10% NOISE RADIATION AT SAY 290 K: 29 K TEMPERATURE INCREASE, AROUND A 3 dB LOSS
  - CONCLUSION: WEATHER IS RISK ABOVE S-BAND (2 GHz)
- EARTH RADIATION INTO ANTENNA CAN BE REDUCED BY QUADRUPOD DESIGN, BECOMES LESS THAN 3 K BACKGROUND
- RECEIVER FRONT-END OPERATES COLD
  - DEPENDING ON QUANTUM-MECHANICAL PRINCIPLE, CAN OPERATE WARMER THAN NOISE TEMPERATURE CONTRIBUTION, E.G., HEMT's

FREQUENCY SELECTION

- HIGHER MICROWAVE FREQUENCIES WITH DIRECTIONAL ANTENNAS RESULT IN MORE RECEIVED SIGNAL POWER, PROPORTIONAL TO SQUARE OF FREQUENCY
  - ANTENNA POINTING HARDER; NEEDED ANGULAR ACCURACY LINEAR IN FREQUENCY FOR FIXED ANTENNA DIAMETERS ON SPACECRAFT AND GROUND
  - SURFACE ACCURACY REQUIRED LINEAR IN FREQUENCY
  - WEATHER EFFECTS ON SYSTEM TEMPERATURE GENERALLY MORE PRONOUNCED AT HIGHER MICROWAVE FREQUENCIES
  - WIND ALSO IMPORTANT FOR GROUND ANTENNA POINTING AT LARGER DIAMETERS AND HIGHER FREQUENCIES
  - PLANET IN RECEIVE BEAM MORE IMPORTANT NOISE SOURCE AS BEAM NARROWS WITH HIGHER FREQUENCIES

- AT VENUS, EXCESS NOISE AT 2 GHz, 70-METER, VENUS CLOSEST APPROACH, IS ABOUT 11 K, BUT AT 32 GHz VENUS FILLS BEAM, 600 K NOISE TEMPERATURE INCREASE

- THUS, ALL OTHER EFFECTS TEND TO REDUCE DATA RATE AS FREQUENCY INCREASES

- NEVERTHELESS, CAREFUL ENGINEERING AND WEATHER STRATEGY MAKE HIGHER FREQUENCIES FOR DEEP SPACE TELEMETRY GOOD INVESTMENT
  - K_a -BAND (32 GHz) LIKELY TO BE HIGHEST FREQUENCY FOR ROUTINE ON-EARTH RECEPTION FOR THREE DECADES

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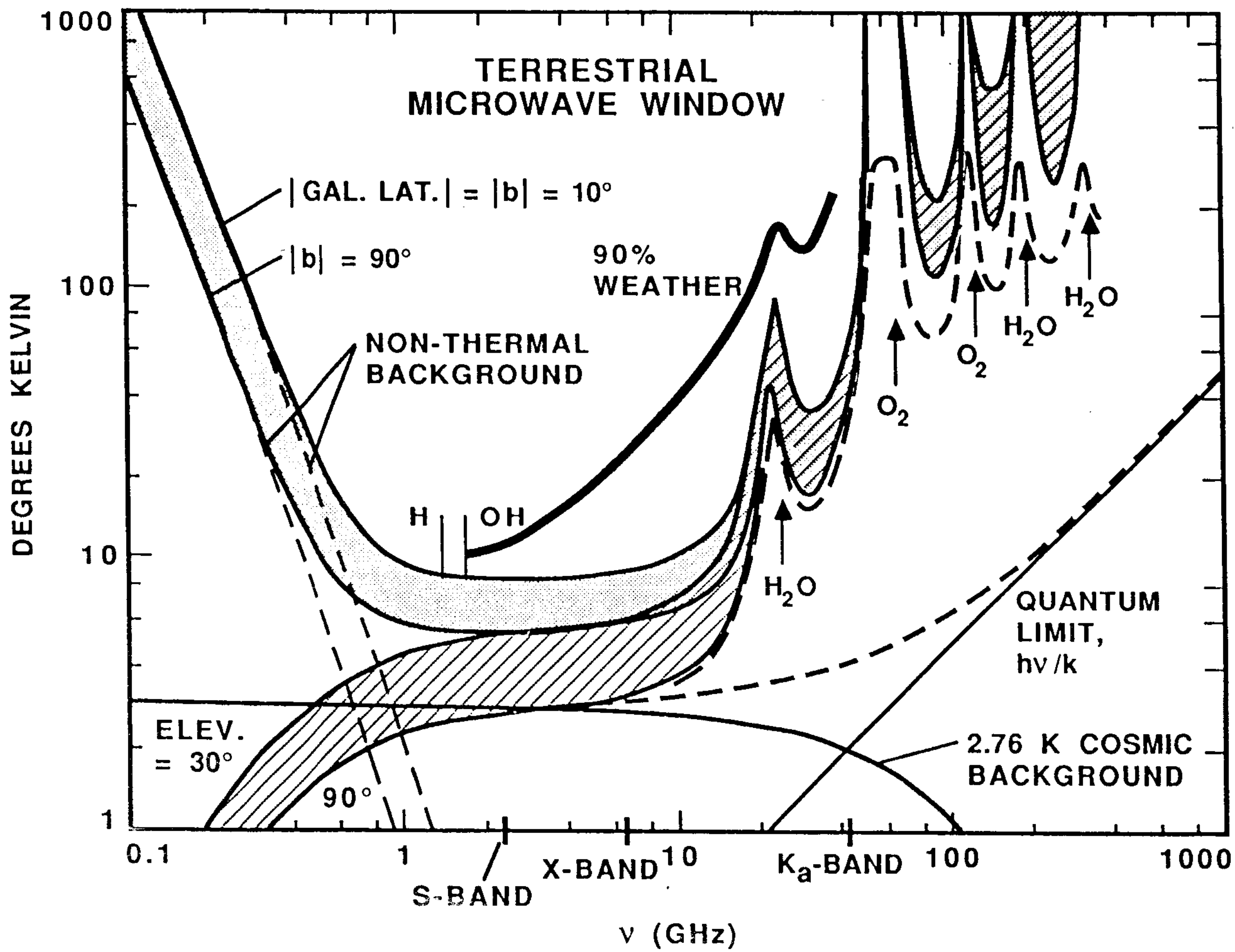

WEATHER EFFECTS

- UNCERTAINTY IN WEATHER AND LONG PROPAGATION DELAYS CAUSE SOME PROBABILITY OF LOSS OF DEEP SPACE DATA AT X-BAND (8.5 GHz) AND HIGHER FREQUENCIES
    - LINK OPERATES WITH STEEP PERFORMANCE CURVE
    - SIGNAL PAD REDUCES AVERAGE DATA RATE
    - WEATHER MODELS NEEDED TO ASSESS RISK
    - VOYAGER AT URANUS AND NEPTUNE WORKED/WILL WORK AT 90% WEATHER CONFIDENCE

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WEATHER EFFECTS (Cont'd)

- WEATHER EFFECTS COULD BE PARTIALLY MITIGATED IN FUTURE BY
  - "BROADCAST" CODING SCHEME WHICH STILL RETURNS SOME DATA EVEN IN ADVERSE WEATHER
  - BETTER WEATHER MODELS
  - MORE ANTENNA DIVERSITY ON GROUND
  - MASSIVE SPACECRAFT DATA STORAGE WITH SELECTIVE RETRANSMISSION
  - RETARGETTING ORBITERS TO FILL IN MISSED AREAS
- WEATHER EFFECTS COULD BE COMPLETELY ELIMINATED BY AN EARTH-ORBITING DEEP SPACE RELAY STATION
- PLANNED MODE OF COPING WITH WEATHER FOR NEXT 20 YEARS INVOLVES
  - BETTER WEATHER MODELS
  - SPACECRAFT DATA STORAGE DEVELOPMENT

CHANNEL CODING AND DATA COMPRESSION

- SHANNON TELLS US THAT A LARGE NUMBER OF BITS SHOULD BE ENCODED INTO A LONG BLOCK OR STRING AND THE RECEIVED WAVEFORM DETECTED AS A UNIT
  - EXTRA POWER THEORETICALLY NEEDED TO DROP BIT ERROR PROBABILITY FROM 10^{-3} TO "ZERO" IS ONLY 0.05 dB
- CODING GAIN RELATIVE TO NO CODING INCREASES AS DESIRED BIT ERROR PROBABILITY DROPS
  - AT 10^{-6} BIT ERROR PROBABILITY, THEORETICAL CODING GAIN ACHIEVABLE IS AROUND 12 dB
- LOW BIT ERROR PROBABILITY FROM DEEP SPACE BECOMING MORE DESIRABLE DUE TO
  - MORE EXTENSIVE USE OF DATA COMPRESSION
  - TREND TOWARD AUTOMATED GROUND OPERATIONS
  - MORE SPACECRAFT INTELLIGENCE WITH AFTER-THE-FACT REPORTING

TELECOMMUNICATIONS AND DATA ACQUISITION

DEEP SPACE COMMUNICATIONS, WEATHER EFFECTS, AND ERROR CONTROL

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CHANNEL CODING AND DATA COMPRESSION (Cont'd)

- CODING COULD INTERACT MORE CLOSELY WITH INSTRUMENTS IN OTHER WAYS THAN JUST THROUGH LOW BIT ERROR PROBABILITY, BY
  - USING SOURCE STATISTICS TO IMPROVE DECODER PERFORMANCE AS IN VOYAGER NEPTUNE VITERBI DECODER BACKUP
  - COMBINED COMPRESSION AND CODING
    - SHANNON TELL US THAT THEORETICAL POWER EFFICIENCY DOES NOT DROP IF COMBINE THE TWO
    - COMPLEXITY CAN DROP GREATLY

C-3

VISIBLE FUTURE TELEMETRY TRENDS

- CODING CLOSER TO SHANNON LIMIT
  - GALILEO CONSTRAINT-LENGTH 15 RATE 1/4 CONVOLUTIONAL CODING DEMO LEADING TO NEW NASA STANDARD CONSTRAINT-LENGTH 15 RATE 1/6 CONVOLUTIONAL CODE
- HIGHER FREQUENCIES: 32 GHz DOWN (K_a-BAND) FOR CASSINI AND MARS ROVER SAMPLE RETURN
- MORE DATA COMPRESSION REQUIRING LOWER BIT ERROR PROBABILITIES
- MUCH MORE MASSIVE SPACECRAFT DATA STORAGE BY LATE 1990's PARTIALLY ALLEVIATING WEATHER EFFECTS PROBLEM
- DEMAND FOR MUCH HIGHER DATA RATES TO ACCOMMODATE INSTRUMENTS SUCH AS IMAGING SPECTROMETERS
  - STILL NEED VERY LOW BIT ERROR PROBABILITIES
  - DECODERS WILL HAVE TO OPERATE FAST
- BEGINNING OF DEEP SPACE TELEMETRY OPERATING NEAR BANDWIDTH LIMITS
  - CONSERVING SIGNAL POWER WILL STILL BE IMPORTANT
  - SUGGESTS COMBINED MODULATION AND CODING

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SUMMARY

- DEEP SPACE TELEMETRY IS AND WILL REMAIN SIGNAL-TO-NOISE LIMITED
- WE DO ALL WE CAN TO INCREASE RECEIVED SIGNAL POWER AND DECREASE NOISE
- WEATHER GREATLY INCREASES NOISE UNPREDICTABLY AT DEEP SPACE FREQUENCIES
- LOW BIT ERROR PROBABILITIES AT HIGH POWER EFFICIENCY OBTAINABLE BY CODING
- FUTURE DEEP SPACE TELEMETRY WILL HAVE EXQUISITELY CODED HIGH BIT RATE HIGHLY COMPRESSED DATA WITH SELECTIVE RETRANSMISSION TO OVERCOME WEATHER EFFECTS
- DEEP SPACE COMMUNICATION OPERATES CLOSER TO THEORETICAL LIMITS THAN ANY OTHER FORM OF COMMUNICATION