Reception of Voyager 1
the best DX ever!

Achim Vollhardt, DH2VA/HB9DUN
Amsat-UK Colloquium 2006
July 29th, 2006
Overview

- Some basics
- Teaming up
- Data Mining
- Calculations+Simulations
- Hardware
- Let’s go!
- Results and Outlook
Some basics

- Deep space probes transmit in X-band: 8400-8450 MHz
- Biphase PSK modulation
- Deep Space Network uses 34&70 m dishes → beyond our capabilities

- ± 90 deg modulation would result in complete carrier suppression
- Probes use 60 or 70 deg: residual carrier (enhances tracking loop robustness in receiver)
- Typical carrier suppressions: -6 or -10 dB
- Amateurs CAN receive this constant carrier with small RX bandwidths and small antennas
First ideas

- Sept '04: Attended lecture of Paul Horowitz at physics conference: “SETI uses Voyager as beacon”
- Asked Jill Tarter for information (director SETI Institute)
- Response by SETI institute member just 24h later!
- James Miller, G3RUH confirmed possibility of detection with Bochum’s 20m dish

- Target date: 30 year anniversary Amsat-DL at Sept 24, 2004 → No success

- Reactivated idea on beginning of March 2006
Pull together the team

- James Miller, G3RUH
- Freddy de Guchteneire, ON6UG
- Hartmut Paesler, DL1YDD
- Achim Vollhardt, DH2VA

And many more..!
Ask the experts!

- Write email to Voyager mission PI: Prof. Edward C. Stone
- Got forwarded via Mission Manager to Mission Telecommunications Analyst Roger Ludwig
- Provided us with valuable and steady flow of information
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From: Ed Stone
Date: March 2, 2006 8:20:26 AM PST
To: Ed Massey
Subject: Fwd: Technical Question to Voyager radio downlink

Ed— I doubt they can detect VGR with an 18 m dish and amateur receivers, but could some one respond to this? Thanks, Ed

Nevertheless .. thank you all!
Deep Space Communications And Navigation Systems Office (descanso.jpl.nasa.gov)

- Has detailed (!) communications link information for multiple deep space missions
- Provided us with almost everything...
Voyager Spacecraft

- Three-axis stabilized s/c
- 3.74 m diameter HGA
- Radioisotopic Thermoelectric Generator (RTG)
- Mission life determined by
  - Hydrazine fuel (2040)
  - RTG power (2020)
  - Funding (4 Mill. USD per year)
- Magnetometer on 13 m long boom
  - Needs to be calibrated about 6 times per year (MAGROL)
Voyager link parameters

- Frequency: 8415.000000 MHz (non-coherent)
  8420.432097 MHz (coherent)
- Polarisation: LHCP (not RHCP!) since failure of TWTA-2 in 1987
- Transmit power: 12/18 W in low/high power mode
- Carrier suppression: -6 dB
- Data rate: 160/1400 bps
- UltraStableOscillator (USO) failed in Sept. 1992, Voyager 1 relies now on crystal AUXOSC
SFOS: space flight operations schedule


| PST | 0   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  | 0   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| UTC | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  | 0   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |

**SIC 31**

INITIAL CONDITIONS
- RTL: 27h 14m 44s
- CGG: A008
- FD: 11AF
- TVNC: ON
- SB: OFF
- XB: HI
- PVR: 05/10/25
- GYROS: OFF

**FCS MODE**
- XB DATA RATE: MI

**DSN COVERAGE**
- 31 0900
- 4015 [D]
- 1610
- 1715
- 10

- 0915
- 0715
- 0515
- 0315
- 0115
- 0015
- 2345
- 0245
- 0045

**TLC (SHORT-FORM)**
- 1400 CCS MEM UID ENA AHEL1
- 1401 1402 CCS MRO
- 1500 XB LOW POWER
- 1604 EAY 1 HTR ON

**GLST**
- 1600(26)
Where are Voyagers today?

- Voyager 1: 98 AU (northbound)
- Voyager 2: 80 AU (southbound)
One-way ‘Radar’ equation

**Standard version:**

Path loss [dB] = \(20 \log(fR) + 20 \log(4\pi/c)\)
= \(20 \log(fR) + (-147.55 \text{ dB})\) \((f=\text{Hz}, R=\text{m})\)

Set \(f=8.4\ \text{GHz}\) and express \(R\) in astronomical units \(\rightarrow\)

**DH2VA version:**

Path loss [dB] = \(20 \log(R) + 274.4 \text{ dB}\) \((R=\text{AU})\)
How to use?

- 1 AU distance  \( \rightarrow \) path loss = 274.4 dB
- 1.5 AU (Venus today)  \( \rightarrow \) path loss = 276.2 dB
- 2.5 AU (Mars Today)  \( \rightarrow \) path loss = 278.8 dB
- 100 AU distance  \( \rightarrow \) path loss = 314.4 dB

1. Find out EIRP of spacecraft carrier:
   Transmit power + antenna gain - carrier suppression
2. Subtract path loss
3. Add RX antenna gain
4. Compare to receiver noise in assumed bandwidth (1 Hz)
5. Result: Signal-to-Noise Ratio in 1 Hz Bandwidth
Transmit side

Find out EIRP of spacecraft (DESCANSO + Google):

- **MRO:**
  
  100 W (50 dBm) + 3m dish (45.5 dBi)  
  carrier suppression -10 dB:  
  = 95.5 dBm (3.5 MW !)  
  85.5 dBm

- **VEX:**
  
  65 W (48.1 dBm) + 1.3m dish (38.3 dBi)  
  carrier suppression -10 dB:  
  = 86.4 dBm (436 kW)  
  76.4 dBm

- **Voyager 1:**
  
  18 W (42.5 dBm) + 3.74 m (48.2 dBi)  
  carrier suppression -6 dB:  
  = 90.7 dBm (1 MW)  
  84.7 dBm
Receive side

- Antenna gain

\[ G = 10^{\log(\eta \cdot (\pi D/\lambda)^2)} \]

- System temperature (Noise figure) \( \rightarrow \) Noise power in 1 Hz

\[ P = k \cdot T_{\text{sys}} \cdot B \]
Results for Bochum

- Diameter: 20 m
- Efficiency: 55%
- Gain: $G = 61.9$ dBi
- Moon noise: 3.3 dB → $T_{sys} = 189$ K
  
  $P = k \times T \times B = -175.8$ dBm

<table>
<thead>
<tr>
<th>spacecraft</th>
<th>EIRP</th>
<th>Path loss</th>
<th>Gain</th>
<th>Noise</th>
<th>SNR (1 Hz)</th>
</tr>
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<tbody>
<tr>
<td>VEX</td>
<td>76.4</td>
<td>276.2</td>
<td>61.9</td>
<td>-175.8</td>
<td>37.9</td>
</tr>
<tr>
<td>MRO</td>
<td>86.5</td>
<td>278.8</td>
<td>61.9</td>
<td>-175.8</td>
<td>45.4</td>
</tr>
<tr>
<td>Voyager 1</td>
<td>84.7</td>
<td>314.4</td>
<td>61.9</td>
<td>-175.8</td>
<td>8.0</td>
</tr>
</tbody>
</table>
Detection principle

- Depending on signal level:
  - 40 dBHz: can be easily heard in speaker
  - 20 dBHz: can be heard with headphones
  - <20 dBHz: requires DSP (soundcard)
  - <10 dBHz: requires integration >1 sec
- Display signal power vs. AF frequency (Fourier display)
- Waterfall display: color code signal strengths and plot one line per integration period
- Integration: average over multiple FFT’s and plot only one line for x FFT’s: noise evens out, while signal persists
Performance Simulation

- G3RUH generated sample WAV files with 3 dBHz (735 seconds) to test analysis techniques
- G3RUH used own analysis package, same algorithm implemented in SCILAB (DH2VA)
  - Record audio samples
  - Perform FFT
  - Add to previous FFT results (integrate)
  - Use 10 Hz convolution filter to compensate for finite VFO step size
- Same algorithm on two different machines and software packages perform equally well and within expectations
System block diagram

- Antenna 20m dia
- Kuhne Pre-amp + Converter
- Synthesiser
- Rubidium Oscillator
- GPS
- UTC
- CAT RS232
- Yaesu FT-736R
- ADC 10 kS/s
- FFT Display
- Audio 0-3 kHz
- RS232 115.2 kb
- 8.4 GHz
- 99.3 MHz
- 1270 MHz
- 10 MHz
- 10^-11
Real world performance

Ground noise
Bad weather
Wet radome
(+ maybe a signal)

Amsat-UK Colloquium 2006
Achim Vollhardt, DH2VA/HB9DUN
Frequency references (I)

Need precise and stable frequency reference!

- **Precision:**
  Is your reading on the VFO is the actual RX frequency?
  → required for finding a signal
  ~ 100 Hz at 8.4 GHz is fine: $10^{-8}$

- **Stability:**
  Is your RX frequency the same for the next 60 seconds?
  → required for long integration times (60 – 1000 seconds)
  ~ 1 Hz at 8.4 GHz = $10^{-10}$ @ $\tau = 1000$ sec
Frequency References (II)

- Well documented, very suitable unit: G3RUH’s GPS stabilised OCXO (check Google...)

- Built with his help two similar units from Ebay-sourced parts

- Or use Rb-normal, if available 😊
Setting everything up
Setting everything up
Setting everything up
The weather

- Light rain (~10 mm/h) with breaks
- Steady winds with gusts > 40kmh
- Temperature 8-16 degC
March 31st, 2006

- Team met at 0600 UTC at the antenna
- Checking MRO’s carrier with ‘wrong’ polarisation: ~18 dBJHz compared to 45 dBJHz the day before (~ 27 dB isolation) → system is sensitive
- Checking around 8415.0000 MHz in steps of 4 kHz with 15 sec integration times
March 31st, 2006

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Result: nothing, nada, nix, null ... just noise!
Again: Ask the experts!

- Last chance: phone the Madrid DSN Tracking Station (scheduled to track Voyager 1 at this very moment with its 70 m dish)

- Problem: How to formulate the question?

- Phone partner #4 was Sergio, the tracking operator

- Frequency was 8420.432 MHz!
THE signal
THE photo
Results of post processing

- G3RUH recorded 15 minutes of WAV files which he analyzed off-line.
- The determined signal strength during our tests was 7.45 dBHz.
- Comparison with pre-test estimation (8.0 dBHz): 0.5 dB deviation.
- Detection should be possible with 2 dB less signal (standard operation mode of Voyager 1).
Future prospects for Bochum

- Replace provisorial installation by a more permanent setup:
  - SMA relay for polarisation switching (septum)!
  - Second LNA for second polarisation
  - Install fixed 10 MHz reference in ground station
  - Permanently lock converter’s LO to reference
- Use HPSDR as receiver (www.hpsdr.org):
  - Remotely controllable
  - 200 kHz detection bandwidth (vs. 3 kHz for FT-736)
  - Future telemetry decoding can be integrated in firmware
  - Coherent signal processing (interferometry?)
- Many more bits and pieces ..
Outlook for individuals

- 20 m for 100 AU distance is equivalent to 20 cm for 1 AU
- Have some signal margin: 60-80 cm SAT-TV dish (Ebay)
- Probes within ca. 1 AU: MRO, VEX, Spitzer, MGS, MEX, NHPC (not much longer)
- Headphones ok for conjunction of Venus and Mars, need soundcard-based DSP for rest of orbits
- GPS stabilised OCXO : Ebay
- Mixer: DB6NT or homemade or Ebay
- LNA: DB6NT or homemade
Amateur-DSN group

- Paul Marsh, M0EYT founded the Amateur-DSN Yahoo group in Dec 2005
- Over 200 members by now and growing
- Few ‘hardcore’ stations (CT1DMK, EB3FRN, M0EYT, F5PL,...)
- Few dozen qrv on 8.4 GHz, same number of stations setting up
- New database lists stations and their equipment
  1 - 5 m dishes are most popular
  GPS stabilised OCXO or Rubidium is rather common
- Details for hardware construction (feeds, filters, ...) online
- Quick and immediate help for newcomers
- Regular reports for several deep space probes
MRO demonstration

ON6UG has prepared a live demo of MRO reception

Check yourself: deep space probes with limited resources IS possible!
Thank you!

"Every vision is a joke until the first man accomplishes it; once realized, it becomes commonplace."

Robert H. Goddard, 1920
pioneer of liquid fueled rocket propulsion