Falcon Gold Experiment Data Processing at The Aerospace Corporation

15 October 1998

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- **Background**
- **Hardware**
- **Data Collection**
- **Signal Processing**
- **Orbit Determination**
- **Conclusions**

Background

- Joint program between the US Air Force Academy ("Falcon") and the University of Colorado ("Gold")
- Further Details on WWW - (Falcon Gold photos from USAFA site)
  - Falcon Gold: http://www.usafa.af.mil/dfas/FalconGold/falcon_gold.html
  - TIDGET Sensor: http://www.navsys.com/tracktag.htm
- Place a GPS sensor in a Geosynchronous Transfer Orbit (GTO)
  - Not a full GPS receiver
  - Digital Sampler or "bit grabber"
  - Sample and characterize (SNR or C/N_0) GPS signals
- Falcon Gold attached to the Centaur upper stage for DSCS-III Flight B13
  - Launched October 24, 1997 from ETR
  - Data collected after DSCS placed in orbit
  - Centaur "dead" during data collection
- Data downlinked to Colorado Springs via radio modem
- In cooperation with NAVSYS and USAFA, Aerospace obtained spacecraft data for processing

Falcon Gold Hardware

- Battery powered
  - 30 Nickel Metal-Hydride (NiMH) cells
  - 15 V DC, 1500-1650 mAh
  - Experiment lifetime maximized by minimizing power consumption
  - 10-15 day predicted battery lifetime
- NAVSYS “TIDGET” sensor
  - samples L-band RF energy for ground post-processing
- Terminal Node Controller
  - Crystal oscillator
- Microcontroller
  - Crystal oscillator
- 2 inch patch antenna
- 9600 baud radio modem

Data Collection

- Experiment activated at T+8000 seconds, after DSCS/IABS separation
- Data collected every five minutes
  - Experiment returned to “sleep mode” between collections to conserve battery power
- Data collected in 40 ms “frames”
  - 1 bit (±1) sampling at 2 MHz
    - 1000 samples per 1023 chip C/A code period
  - 80,000 bits per 40 ms frame
  - Downlinked in 40 “segments” of 1 ms each
- Time span of Falcon Gold data obtained by Aerospace
  - First Frame 3 November
  - Last Frame 9 November
  - Approximately 1700 data collection opportunities
- Data downlink possible only when
  - Falcon Gold in view of Colorado Springs
  - Slowly tumbling Centaur points downlink antenna at ground station

Falcon Gold Data Features

- Centaur “dead” during data collection
  - No Centaur attitude information
  - No attitude control
  - No RTS/SGLS tracking
  - NORAD tracking and element sets only ephemeris knowledge
- Large perturbations affecting Centaur orbit
  - Centaur “blowdown” maneuvers
  - Solar radiation pressure at high altitude
  - Drag at low altitude
- Data Timetags had large (4+ minutes) biases
  - Noticed inconsistency in timing and known geometry
  - Operators confirm timetag offsets on the order of minutes
- All Falcon Gold data frames obtained by Aerospace were “fragmented”
  - No complete 40 ms frames
  - Missing segments originally replaced with (10101) “filler” data
  - Aerospace processed “good” fragments only

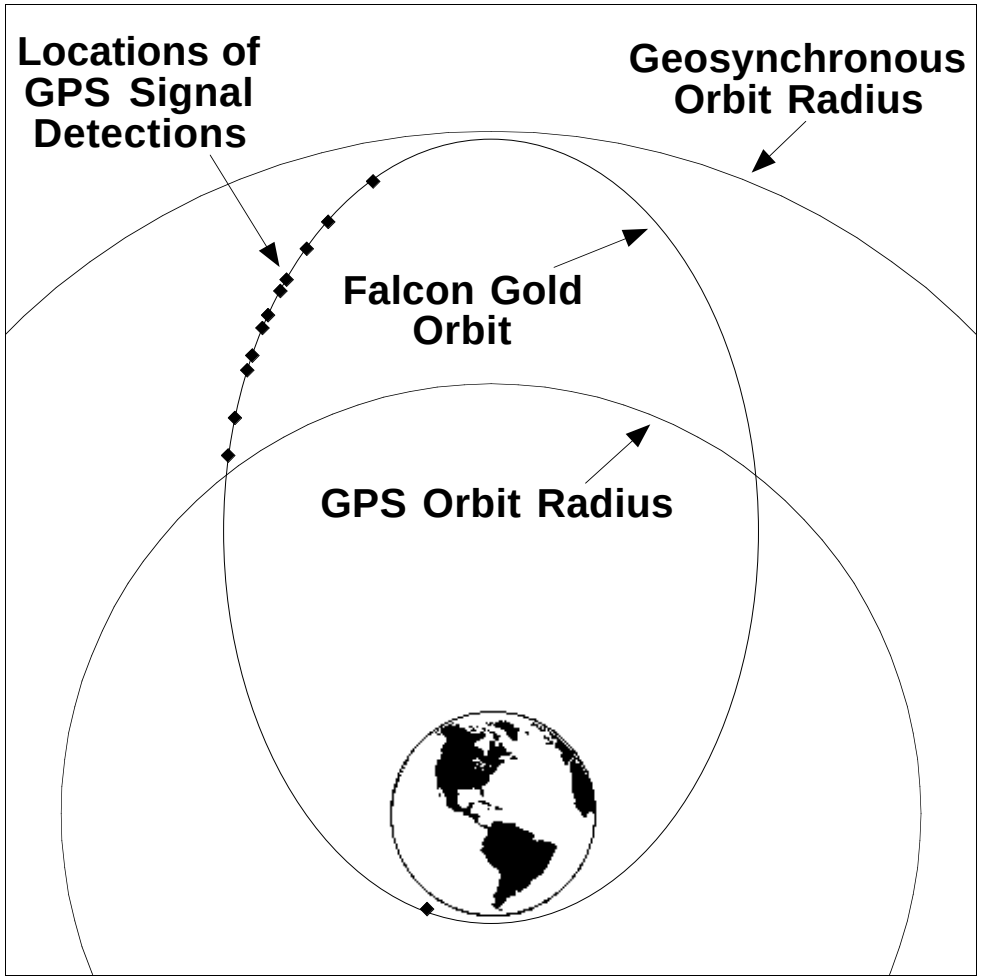
Signal Processing

- Signal processing technique verified with balloon flight test data
  - Duplicated NAVSYS results on balloon data
- Emphasis on PRN detection, signal strength and geometry rather than pseudorange computation
- Comprehensive search over GPS C/A code PRN's and Doppler shift
- TIDGET downconverts GPS L_1 prior to 2 MHz sampling
  - GPS C/A code frequency 1.023 MHz
  - Final TIDGET IF = 4.30888 MHz
- Signal Detection based on correlation function
  - Detection function related to Normal random variable
  - Conservative, "5-σ" threshold used to minimize probability of false detection
- Correlation Process Outputs
  - Detected PRN's
  - Intermediate Frequency (IF)
  - Correlation Power

Overview of Falcon Gold Orbit Geometry and TIDGET Data Statistics

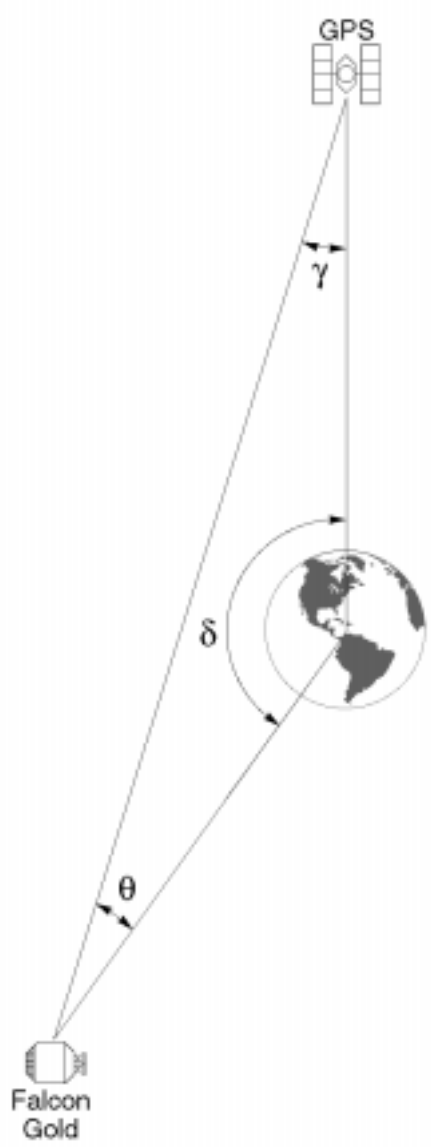
- 1700+ data collection opportunities (3 Nov - 9 Nov)
- 100 Data Frames Obtained
  - 73 Valid Timetags
- 432 Total Data Fragments
  - 357 “good” Fragments
- GPS Signals Detected in 12 of the “good” Fragments
  - Total of 25 Individual PRN’s Detected

Falcon Gold Final Orbit Parameters	
Semi-Major Axis:	24070 km
Eccentricity:	0.7275
Inclination:	26.296 deg
RAAN:	210.4 deg
Arg. of Perigee:	186.7 deg
Apogee Altitude:	35200 km
Perigee Altitude:	181 km



GPS Signal Detection Summary and Angular Definitions

GPS Signal Detection Summary									
		Earth/Centaur/GPS Angle Values			Observed and Geometrically Predicted Detection Parameters				
Frame Number	PRN	δ (deg)	θ (deg)	γ (deg)	Geometric Range (Earth radii)	Geometric Range Rate (m/sec)	Observed Range Rate (m/sec)	Range Rate Residual (m/sec)	Observed $\frac{C}{N_o}$ (dB)
3643-2	16	153.5	10.8	15.7	9.89	-734.70	-734.74	0.04	34.88
3646-1	16	155.4	10.2	14.4	9.74	-1163.52	-1161.67	-1.85	36.17
3649-2	16	155.2	10.5	14.3	9.53	-1600.62	-1599.27	-1.35	37.92
	27	154.7	10.7	14.6	9.48	-999.95	-1000.95	1.00	37.39
3650-2	16	154.7	10.8	14.5	9.45	-1747.16	-1746.66	-0.50	32.79
3652-1	4	147.0	14.4	18.7	9.12	-1651.22	-1650.11	-1.11	34.25
	16	153.1	11.7	15.2	9.26	-2040.17	-2044.10	3.93	34.28
3653-2	4	146.8	14.6	18.6	9.04	-1837.40	-1839.97	2.57	30.41
	16	152.0	12.3	15.7	9.15	-2186.14	-2188.44	2.30	35.90
	19	154.2	11.3	14.4	9.19	-2252.91	-2254.14	1.22	35.64
	29	78.1	42.8	59.0	6.01	-2617.86	-2618.99	1.13	30.56
3655-4	19	151.3	12.9	15.8	8.95	-2430.47	-2432.37	1.90	33.48
3656-2	4	144.8	15.9	19.2	8.71	-2392.49	-2392.96	0.47	34.81
	16	147.9	14.6	17.5	8.79	-2617.94	-2619.94	2.00	34.60
3659-2	16	142.8	17.5	19.7	8.36	-3033.71	-3037.35	3.64	33.90
	19	145.9	16.1	18.1	8.43	-2735.94	-2734.58	-1.37	35.41
3982-8	23	149.5	12.1	18.4	10.08	-503.84	-514.04	10.20	36.23
4006-1	21	153.1	13.2	13.8	8.40	-3011.25	-3021.55	10.30	39.16
4024-2	3	96.1	67.8	16.1	4.46	-3100.47	-3102.67	2.20	41.52
	15	50.2	113.9	15.9	3.50	-5756.76	-5763.25	6.48	42.00
	21	109.0	56.7	14.3	4.76	-4057.18	-4061.45	4.27	41.19
	22	108.3	57.3	14.4	4.75	-7999.04	-8008.12	9.08	42.91
	23	106.9	58.5	14.6	4.72	105.68	105.42	0.26	41.17
	27	28.9	139.9	11.1	3.11	5013.55	5015.77	-2.21	37.11
	31	62.1	100.8	17.1	3.73	-798.46	-797.39	-1.07	42.72



Frame 3982-8 Detail

Frame Number 3982, Fragment Number 8	
Original Timetag:	11/8/1997 22:59:52.000
Corrected Timetag:	11/8/1997 22:55:21.297
Timetag Correction:	270.7 sec
Number of data bytes: 2196	Number of bits processed: 16000 (8.0 ms)
Centaur True Anomaly:	189.9 deg
Centaur Altitude:	33593.6 km (13411.7 km above GPS)

GPS Signal Detection Summary

	Earth/Centaur/GPS Angle Values			Observed and Geometrically Predicted Detection Parameters				
PRN	δ (deg)	θ (deg)	γ (deg)	Geometric Range (Earth radii)	Geometric Range Rate (m/sec)	Observed Range Rate (m/sec)	Range Rate Residual (m/sec)	Observed $\frac{C}{N_o}$ (dB)
23	149.5	12.1	18.4	10.08	-503.84	-514.04	10.20	36.23

Frame 4024-2 Detail

Frame Number 4024, Fragment Number 2	
Original Timetag:	11/9/1997 02:45:52.000
Corrected Timetag:	11/9/1997 02:41:23.917
Timetag Correction:	268.1 sec
Number of data bytes: 2196	Number of bits processed: 16000 (8.0 ms)
Centaur True Anomaly:	306.1 deg
Centaur Altitude:	1550.8 km (18631.0 km below GPS)

GPS Signal Detection Summary

	Earth/Centaur/GPS Angle Values			Observed and Geometrically Predicted Detection Parameters				
PRN	δ (deg)	θ (deg)	γ (deg)	Geometric Range (Earth radii)	Geometric Range Rate (m/sec)	Observed Range Rate (m/sec)	Range Rate Residual (m/sec)	Observed $\frac{C}{N_o}$ (dB)
3	96.1	67.8	16.1	4.46	-3100.47	-3102.67	2.20	41.52
15	50.2	113.9	15.9	3.50	-5756.76	-5763.25	6.48	42.00
21	109.0	56.7	14.3	4.76	-4057.18	-4061.45	4.27	41.19
22	108.3	57.3	14.4	4.75	-7999.04	-8008.12	9.08	42.91
23	106.9	58.5	14.6	4.72	105.68	105.42	0.26	41.17
27	28.9	139.9	11.1	3.11	5013.55	5015.77	-2.21	37.11
31	62.1	100.8	17.1	3.73	-798.46	-797.39	-1.07	42.72

Frame 3653-2 Detail

Frame Number 3653, Fragment Number 2	
Original Timetag:	11/7/1997 17:29:27.000
Corrected Timetag:	11/7/1997 17:24:35.771
Timetag Correction:	291.2 sec
Number of data bytes: 8588	Number of bits processed: 68000 (34.0 ms)
Centaur True Anomaly:	204.3 deg
Centaur Altitude:	27243.8 km (7061.9 km above GPS)

GPS Signal Detection Summary

	Earth/Centaur/GPS Angle Values			Observed and Geometrically Predicted Detection Parameters				
PRN	δ (deg)	θ (deg)	γ (deg)	Geometric Range (Earth radii)	Geometric Range Rate (m/sec)	Observed Range Rate (m/sec)	Range Rate Residual (m/sec)	Observed $\frac{C}{N_o}$ (dB)
4	146.8	14.6	18.6	9.04	-1837.40	-1839.97	2.57	30.41
16	152.0	12.3	15.7	9.15	-2186.14	-2188.44	2.30	35.90
19	154.2	11.3	14.4	9.19	-2252.91	-2254.14	1.22	35.64
29	78.1	42.8	59.0	6.01	-2617.86	-2618.99	1.13	30.56

Orbit Determination

- Refined *a priori* NORAD orbit using Doppler range rate to detected GPS Spacecraft and NIMA Precise GPS Ephemerides
- Solved for a timetag bias and drift rate to account for drift of onboard crystal oscillators
- Performed least squares orbit fit using TRACE
  - Range rates derived from the correlation processing
  - Measurements weighted proportionally to fragment length
  - Solved for Centaur position, velocity, solar radiation pressure, drag, and range rate bias
- Geometric studies using resulting orbit
  - Confirm visibility of detected PRN's
  - Compute predicted range rate, or equivalently, Doppler shift
  - Compute predicted C/N_0 using approximated gain patterns

Data Processing Results

- GPS Signals detected in 12 frames
- Total of 25 PRN's confirmed
- Detection altitudes from 1500 km to 33000 km
  - 18000 km below GPS to 10000 km above GPS
- Carrier to Noise ratios (C/N_0) from 30 to 42 dB
- Detections confirmed with known GPS constellation geometry
- A GPS side lobe signal apparently detected in Frame Number 3659
- GLONASS signal also apparently detected, further analysis TBD

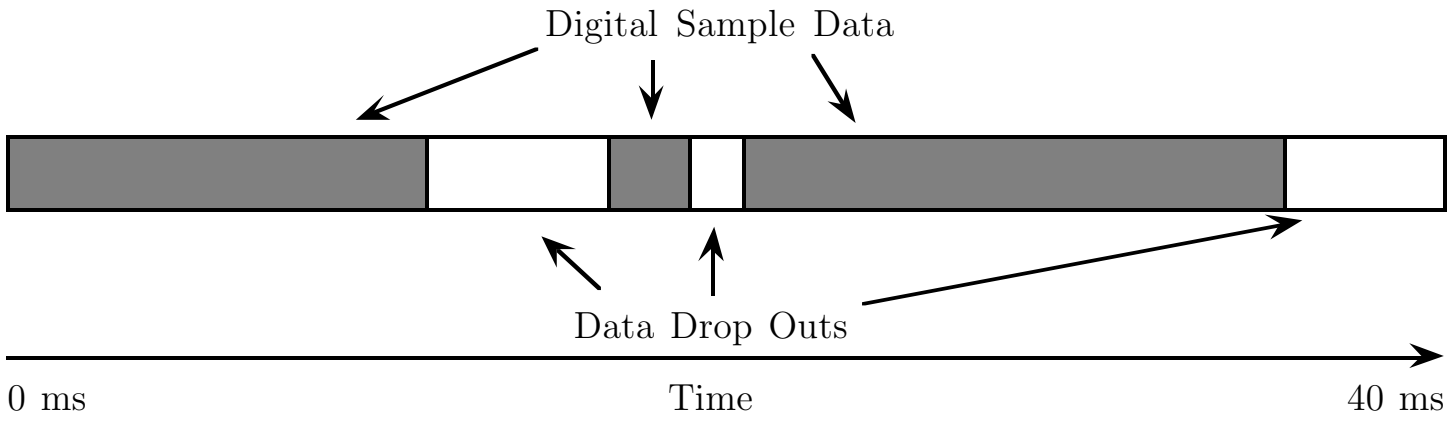
Conclusions

- GPS signals can be detected in a highly eccentric orbit with apogee approaching geosynchronous altitude
- This capability was demonstrated with
  - 2 inch patch antenna
  - "Bit grabber" sensor - NAVSYS TIDGET
  - Ground based post-processing
  - GPS signals were <u>not</u> continuously tracked in real time
- GPS signals detected under very sparse sampling conditions
  - 1-bit sampling at 2 MHz
  - Signals detected in fragments as short as 4 milliseconds
  - Signals detected at distances up to 10 Earth radii
- Results of this experiment consistent with the concept of navigating high altitude spacecraft with GPS
- Further experimentation and analysis are necessary

BACKUP SLIDES

Falcon Gold Data Frame Fragmentation

Distribution of Falcon Gold Data Fragment Sizes	
Fragment Duration	Number
0 – 5 ms	278
5 – 10 ms	40
10 – 15 ms	14
15 – 20 ms	13
20 – 25 ms	3
25 – 30 ms	4
30 – 35 ms	5



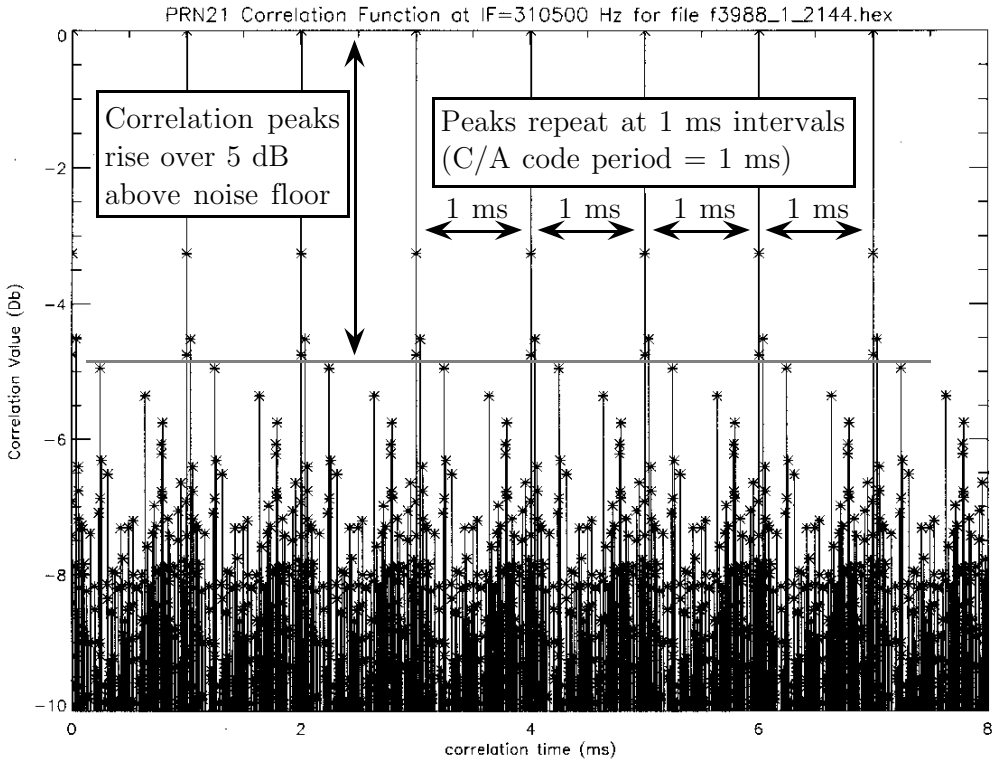
Signal Processing Notes

Transmitted signal: $S = \{s_1, s_2, \ldots, s_n\}$
Received signal: $R = \alpha S + N$

Detection Criterion, 'Power Ratio': $P = \frac{(S,R)^2}{R^2} > \mathcal{T}^2$
Detection Threshold: $\mathcal{T} = 5 \rightarrow P_{fa} \approx 6 \cdot 10^{-7}$

Signal Strength Relationships:
$\frac{C}{N_0} = \frac{SNR}{dt} = \frac{P-1}{T}$

Falcon Gold GPS Signal Detection Example



Approximated GPS II-A Transmit Antenna and Falcon Gold Patch Antenna Gains