

APPLICATION OF FUNCTIONAL TIME BASED COMPRESSION TO SATELLITE TELEMETRY

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Abstract

Usually, the evolution of a signal is described using a table that provides raw time and signal measurements (time can be implicit). Such a representation has a high a priori redundancy. Standard data compression methods preserve the tabular format, and therefore do not reduce the a priori redundancy.

Functional time-based compression (FTC) is designed to reduce (and for all practical purposes minimize) this redundancy by replacing raw data with a few coefficients that are obtained through curve fitting. The independent variable is time. In other words, FTC represents signals as functions of time. FTC can be used for both transmission and storage of non-random data. To show the potential of this method, FTC was applied to Extreme Ultraviolet Explorer (EUVE) telemetry. Satellite telemetry links use the conventional table format to transmit time and sensor measurements. FTC replaces bulky tables of ephemeris, Sun sensor and magnetometer measurements with coefficients for Legendre polynomials. The ground station would retrieve original measurements calculating the values of Legendre polynomials at desired times. These polynomial functions that are time-based, describe the evolution of various signals for up to several minutes. Results show that FTC reduces storage capacity or transmission bandwidth by an order of magnitude, while assuring verbatim representation of data. For higher reduction, compression should be combined with data smoothing.

1. Introduction

Data compression allows broadcasting systems to transmit more information over existing channels and archival facilities to use less storage capacity. Therefore, the same number of satellites would provide more data, or the number of satellites (including communication satellites) could be reduced. Finally, for missions that experience communication problems,

data compression could mean the difference between failure and success.

Current data transmission and archival systems use a tabular representation, i.e., signals such as ephemeris, Sun angle and magnetic field intensity are sampled at regular intervals and included in tables. The measurement time may also be included. See table 1 for an example of tabular representation. In this form, the evolution of Sun angle over a period of 2 seconds is described using $21 \times 2 = 42$ numbers. A total of 168 bytes are required to transmit these numbers in single precision.

Time-based curve fitting reveals how wasteful is the tabular representation. A signal representation that is ideal, i.e., has no redundancy, requires a crystal clear understanding of all physical phenomena involved in the measurement process. Such clear understanding is usually lacking, which explains the need for measurements. Nevertheless, FTC provides a description that comes close to the ideal. Curve fitting that is based on time, shows that data from Table 1 obeys the following law:

$$S(t) = S_0 + (dS/dt)_0 \cdot t \quad (1)$$

During the first second, $S_0 = 10$ and $(dS/dt)_0 = 0.2$. Therefore, only two numbers, i.e., 10 and 0.2 need to be transmitted or archived in order to describe the signal evolution over this period. For the next second, $S_0 = 12$ and $(dS/dt)_0 = -0.3$. Therefore, 4 coefficients and two initial times can describe the signal evolution over the entire period. FTC results are shown in Table 2. There is no redundancy in this representation; i.e., FTC minimizes data entropy.

FTC results can be transmitted or archived using only 24 bytes, while raw data (see table 1) requires 168 bytes. In other words, here FTC provides a compression ratio of 7 to 1 with no precision loss. This reduction is possible because Table 1 contains 36 redundant numbers, out of a total of 42 i.e., 86%. The end user retrieves raw Sun angles using equation (1) and Table 2.

Table 1. Sun sensor data represented in typical tabular form

Time (s)	Sun angle, S, (deg)
0	10
0.1	10.2
0.2	10.4
0.3	10.6
0.4	10.8
0.5	11.0
0.6	11.2
0.7	11.4
0.8	11.6
0.9	11.8
1.0	12
1.1	12
1.2	11.7
1.3	11.4
1.4	11.1
1.5	10.8
1.6	10.5
1.7	10.2
1.8	9.9
1.9	9.6
2.0	9.3

Table 2. Representation of Sun sensor data having minimum entropy and determined using FTC.

Time when coefficients become applicable (s)	S ₀	(dS/dt) ₀
0.0	10.0	0.2
1.0	12	-0.3

FTC can be used in conjunction with usual compression methods. For example, the zip-compression of FTC coefficients would yield an overall compression ratio of about 14:1.

FTC trades computer-processing time for bandwidth. Bandwidth is limited and as any commodity that is in short supply can be expected to become more expensive, while the ratio of computer power versus price is rapidly increasing. Therefore, the trade-off required by FTC is highly advantageous.

Equation (1) is useful only for a restricted number of data sets. For attitude sensors, a more general fitting equation is recommended, for example Legendre polynomials¹, $P_l^m(t_s)$, where the scaled time, t_s , is given by:

$$t_s = \frac{t}{t_{total}}$$

and t_{total} is the validity period for the Legendre representation.

The first three Legendre polynomials are listed in Table 3. Higher order Legendre polynomials can be calculated by recurrence. Recurrences on order, m , are unstable, therefore recurrence on degree, l , is recommended¹:

$$(l - m)P_l^m = x(2l - 1)P_{l-1}^m - (l + m - 1)P_{l-2}^m \quad (2)$$

Signals and signal derivatives with respect to time are expected to exhibit some discontinuities. As a consequence, raw data has to be divided into subintervals. Two intervals were used for Sun angle data. Each interval spanned one second, i.e., t_{total} , was 1 second for both.

For a subinterval, the measurements provided by an attitude sensor can be expressed as:

$$S(t) = \sum_{l=0}^L c_l P_l^0 \left(\frac{t}{t_{total}} \right) \quad (3)$$

Table 3. Low order Legendre polynomials, P_l^m

m	l	P_l^m
0	0	1
0	1	t_s
1	1	$-(1-t_s^2)^{1/2}$

Table 4. Sample of current satellite telemetry

Time	CSS (counts)	DSS (counts)	x-axis magnetic field (counts)....
t_1	$n_{CSS}(t_1)$	$n_{DSS}(t_1)$	$n_{TAM-x}(t_1)$
t_2	$n_{CSS}(t_2)$	$n_{DSS}(t_2)$	$n_{TAM-x}(t_2)$
...			
t_m	$n_{CSS}(t_m)$	$n_{DSS}(t_m)$	$n_{TAM-x}(t_2)$

The Legendre coefficients, c_l , are determined using a least-square algorithm¹.

Experiments have shown that little can be gained using l values in excess of 6. Increased data compression ratios could be achieved using a library of fitting functions that includes at least Chebyshev polynomials and Fourier transforms. If such a library is used, a flag indicating the function type should be added to the data listed in Table 2. Commercial curve-fitting software includes an extended library of fitting functions (up to several thousand functions). This software provides the fitting coefficients and the accuracy of the fit. With minimal modifications, commercial of the shelf software would provide the best possible fit for most satellite data. Such sophisticated software might strain the on-board processors, but not the ground computers.

Although applied here to satellite telemetry, FTC is by no means restricted to spacecraft applications. FTC could just as easily process HDTV², phone, radio, High Fidelity audio signals, biomedical and wind tunnel measurements, data collected in engine testing facilities and so on. In fact, any non-random signal can be compressed or encrypted using this method.

2. Numerical Approach

The Extreme Ultraviolet Explorer (EUVE) mission was to provide the definitive sky map and catalog in the electromagnetic spectrum extending from approximately 100 to 1000 angstroms³. The EUVE complement of attitude sensors consists of 2 fixed head star trackers (FHST), 2 fine Sun sensors (FSS), an inertial reference unit with 6 channels (i.e.,

gyros), 2 three Axis Magnetometers (TAM), a magnetic torquer assembly and a reaction wheel assembly. FTC was applied to Sun, Moon and spacecraft ephemeris and to FHST, FSS, TAM, gyro and quaternion data. Currently, satellite telemetry is structured as shown in Table 4. Before applying FTC, data were separated according to type. FTC was carried out by a FORTRAN code based on equation (2) and (3). Data decompression was performed using a similar code based on equation (3).

FTC was applied to the first 200 frames of EUVE telemetry from December 16 1992. This telemetry includes 204 seconds worth of ephemeris and attitude data. A 166 MHz Pentium PC compressed ephemeris data in about 70. FSS and TAM data required another 70 seconds. Three minutes were needed to process the quaternions. Star tracker and gyro data also required a couple of minutes. Therefore, parallel processing is recommended for real-time applications.

3. Results and Discussion

Unless otherwise specified, FTC preserved verbatim data representation (i.e., the original and decompressed data are identical). The compression ratio is calculated dividing the size (in bytes) of the file containing raw data by the size of the file with curve-fit coefficients.

Figure 1 shows the size of uncompressed and compressed position vectors (in bytes). All ephemeris data are expressed in January 2000 Geocentric Inertial Coordinates, (GCI). The compression ratios are 5.3:1, 5.7:1 and 8.3:1 for x-, y-, and z-axis coordinate, respectively.

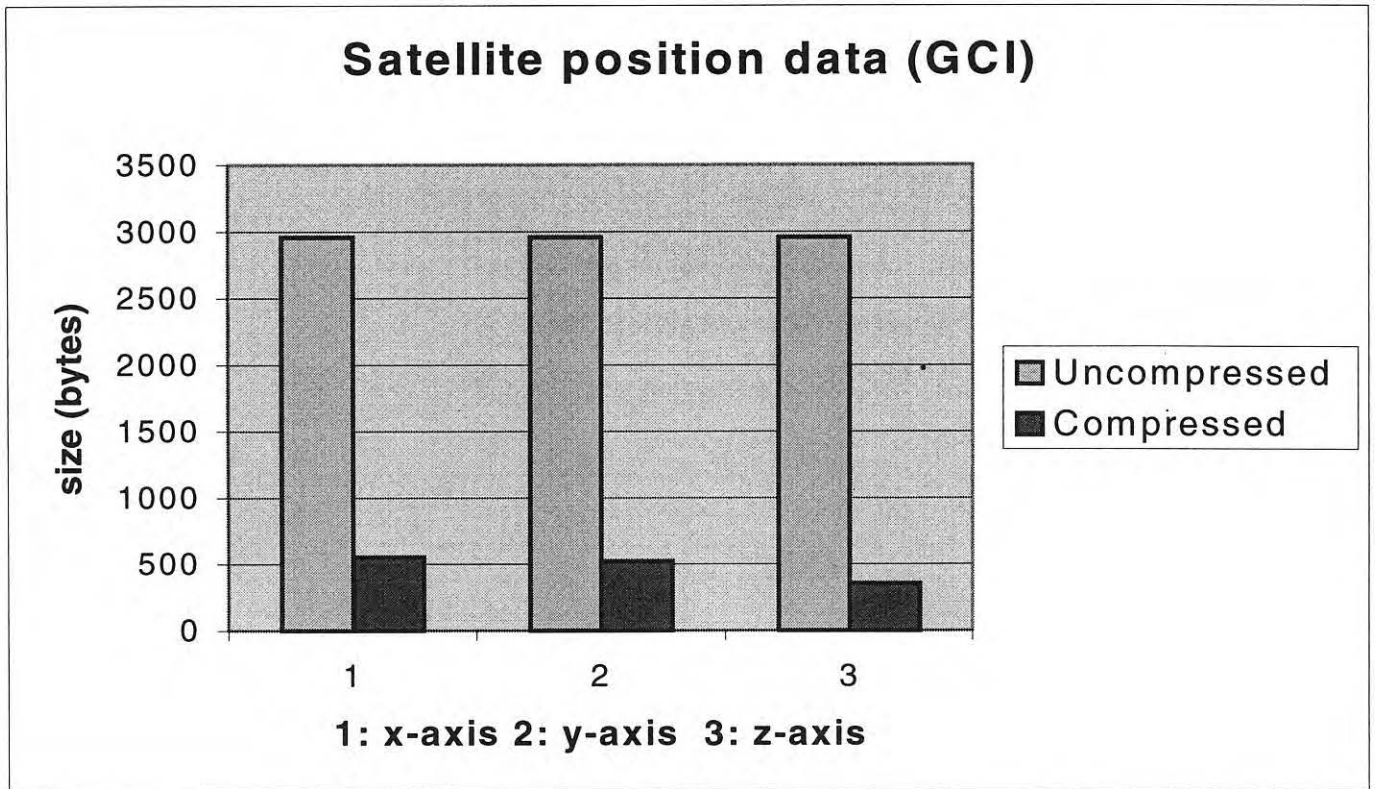


Fig.1. Compression ratio using FTC for Extreme Ultraviolet Explorer position data

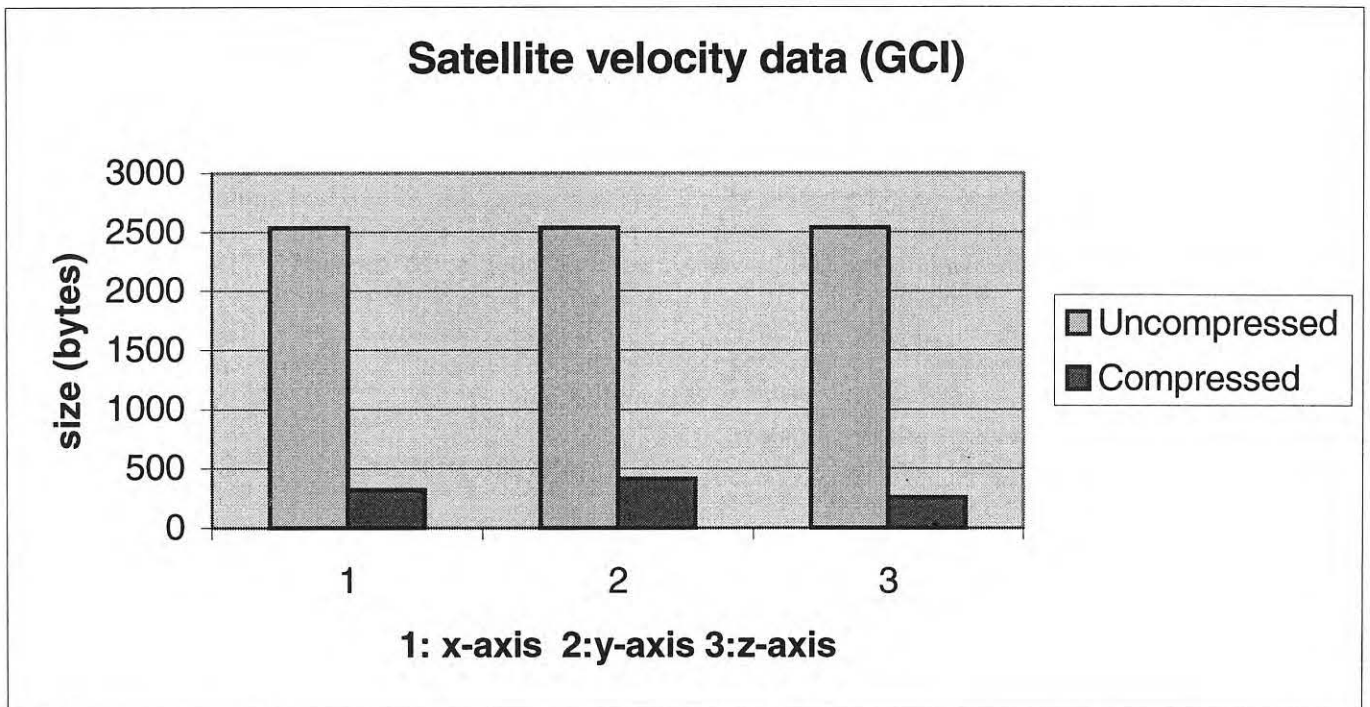


Fig.2. Compression ratio using FTC for Extreme Ultraviolet Explorer velocity data

Results for velocity are shown in Figure 2. The compression ratios are 7.8:1, 6.1:1 and 20.1:1 for the x, y, and z-axis component, respectively.

EUVE telemetry reserves 6 digits for satellite coordinates and only 4 for velocity components. As a consequence, verbatim FTC yields higher compression

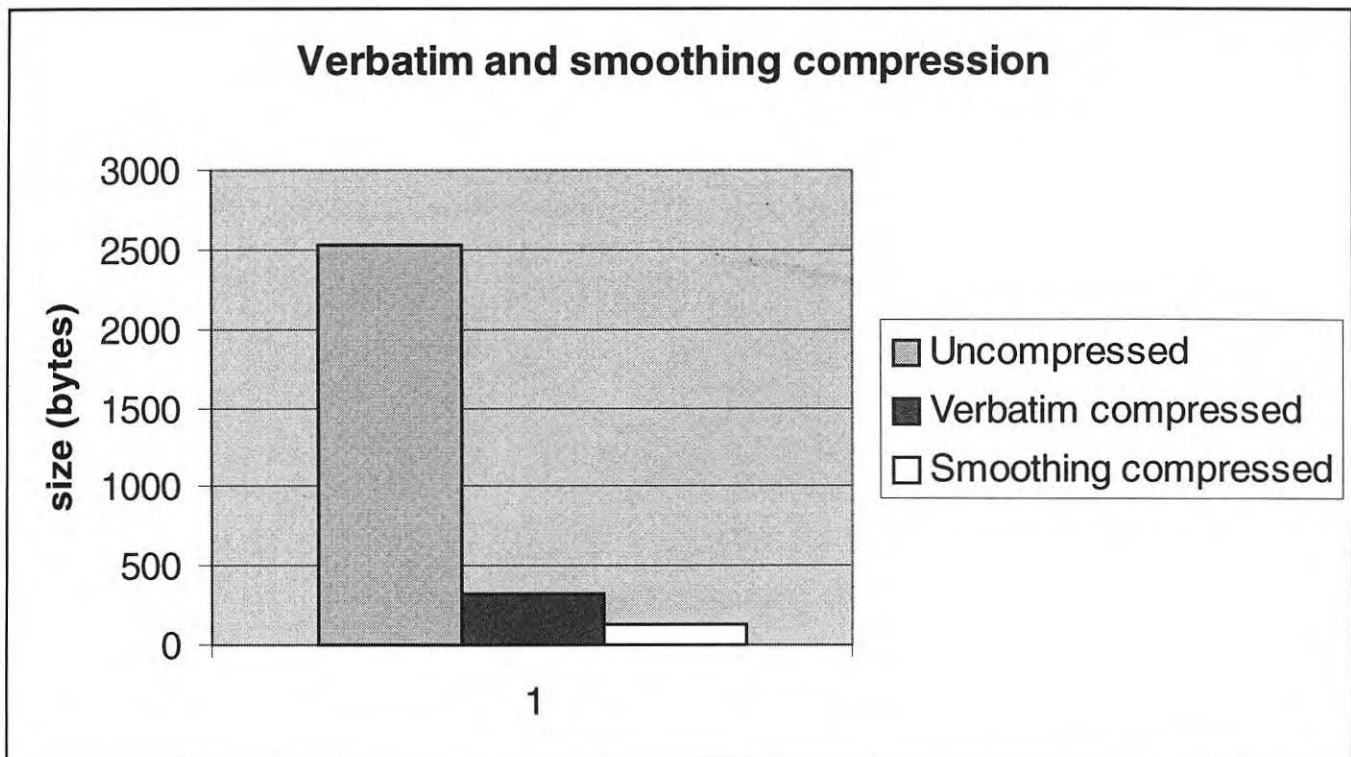


Fig.3. Compression ratio using verbatim and smoothing FTC for Extreme Ultraviolet Explorer x-axis component of velocity

ratios for velocity.

FTC can also be used to smooth raw data. In this case, FCT eliminates round off errors and noise and yields higher compression ratios. Figure 3, shows the results for x velocity data. The compression ratio for smoothing and verbatim representation is 23.1:1 and 16.1:1, respectively. In addition, whenever combined with zip techniques that are applied to curve fit coefficients instead of raw measurements, FTC yields overall compression ratios that exceed 10.0: 1 for most spacecraft ephemeris.

For Sun and Moon ephemeris, which are included as reference data, EUVE telemetry reserves 6 and 4 digits, respectively. Nevertheless, because the evolution of the Sun vector is very smooth, similar compression ratios are achieved for both Sun and Moon ephemeris. Figure 4 shows the results for Moon data. The compression ratio for x-, y- and z-coordinate is 12.7:1, 25.0:1 and 14.2:1, respectively. Results for Sun ephemeris are shown in Fig. 5. In this case, the compression ratio for x-, y- and z-coordinate is 29.5:1, 32.0:1 and 11.8:1, respectively. In conjunction with conventional techniques, FTC would boost the compression ratios for Sun and Moon ephemeris up to 100.0:1.

Figure 6 shows FTC results for FSS data. The EUVE telemetry provides the Sun unit vector, not Sun angles. The x component of this vector has a smooth evolution. As a consequence, the compression ratio for x is 46.5:1. For both y and z components the ratio is 4.5:1. Combining FTC with conventional methods would again boost the overall ratio to about 10.0:1 for y and z components and 100.0:1 for the x component.

FTC results for magnetic field measurements are shown in Fig 7. EUVE TAMs measure the x, y and z component of the geomagnetic field. The compression ratio is 7.2:1, 11.1:1 and 5.9:1 for the x, y and z component, respectively.

Using Legendre polynomials, verbatim FTC provides no compression for star tracker, gyro and quaternion data. Fixed Head Star Tracker (FHST) data is included as a unit vector with 7 digits for each component. The least significant bit (LSB) has a value of 0.02 arc-seconds. As shown in a previous study by the author⁴, FHST star trackers have an accuracy of about 15 arc-seconds (1σ). In other words, the last 3 digits allocated to FHST measurements are meaningless. As discussed in section 1, FTC does not compress random noise. The number of digits used for EUVE gyro data is also too large given the

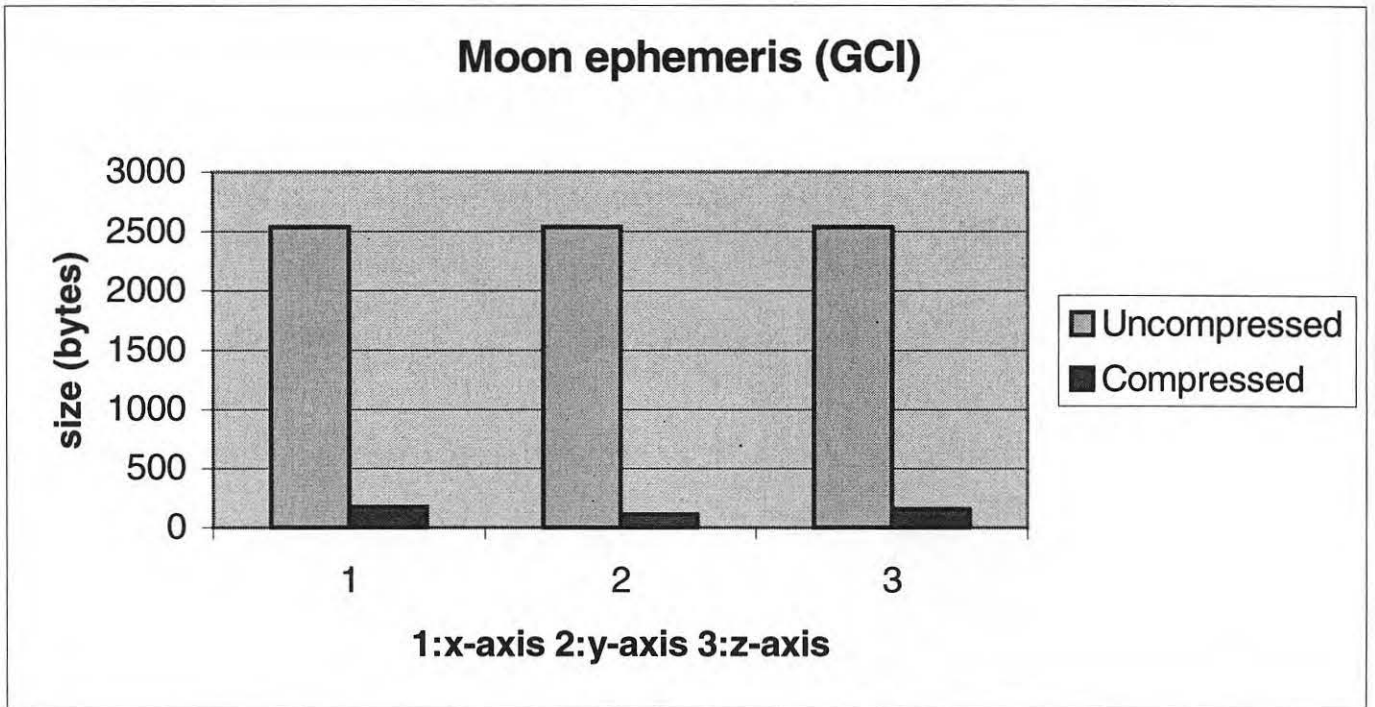


Fig 4. Compression ratio using FTC for Moon ephemeris data

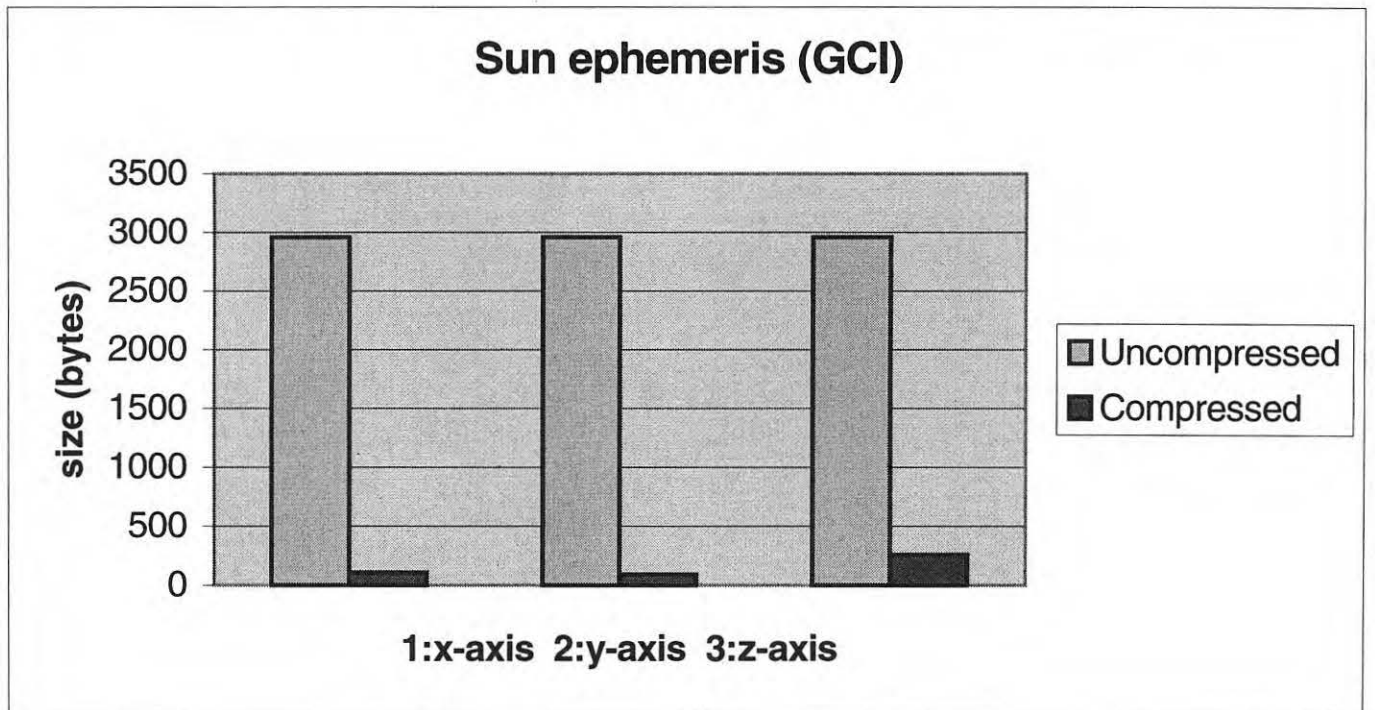


Fig 5. Compression ratio using FTC for Sun ephemeris data

accuracy of these gyros. Quaternion accuracy was limited by FHST and gyro noise. Only the first 4 digits (out of a total of 8) are meaningful. It remains to be seen if other functions are better suited than

Legendre polynomials for compression of noisy data, or if smoothing FTC is required, whenever the LSB and noise level are comparable.

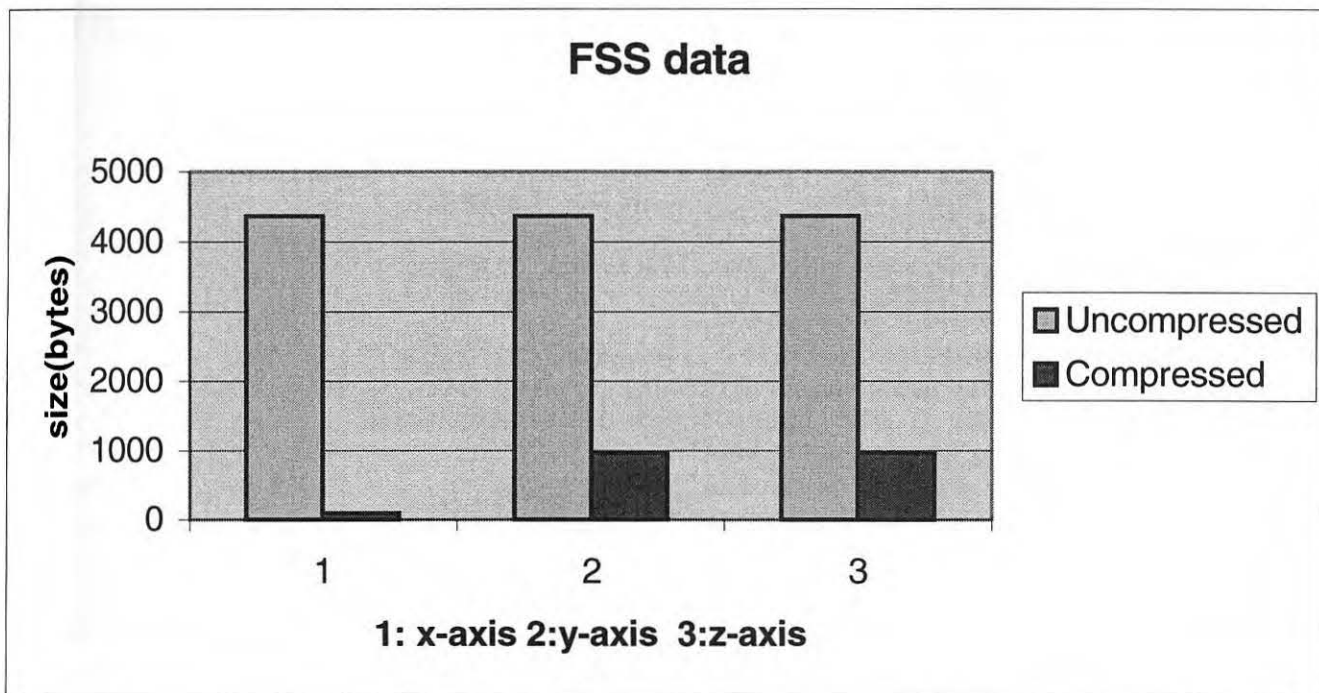


Fig.6. Compression ratio using FTC for Extreme Ultraviolet Explorer Fine Sun Sensor data

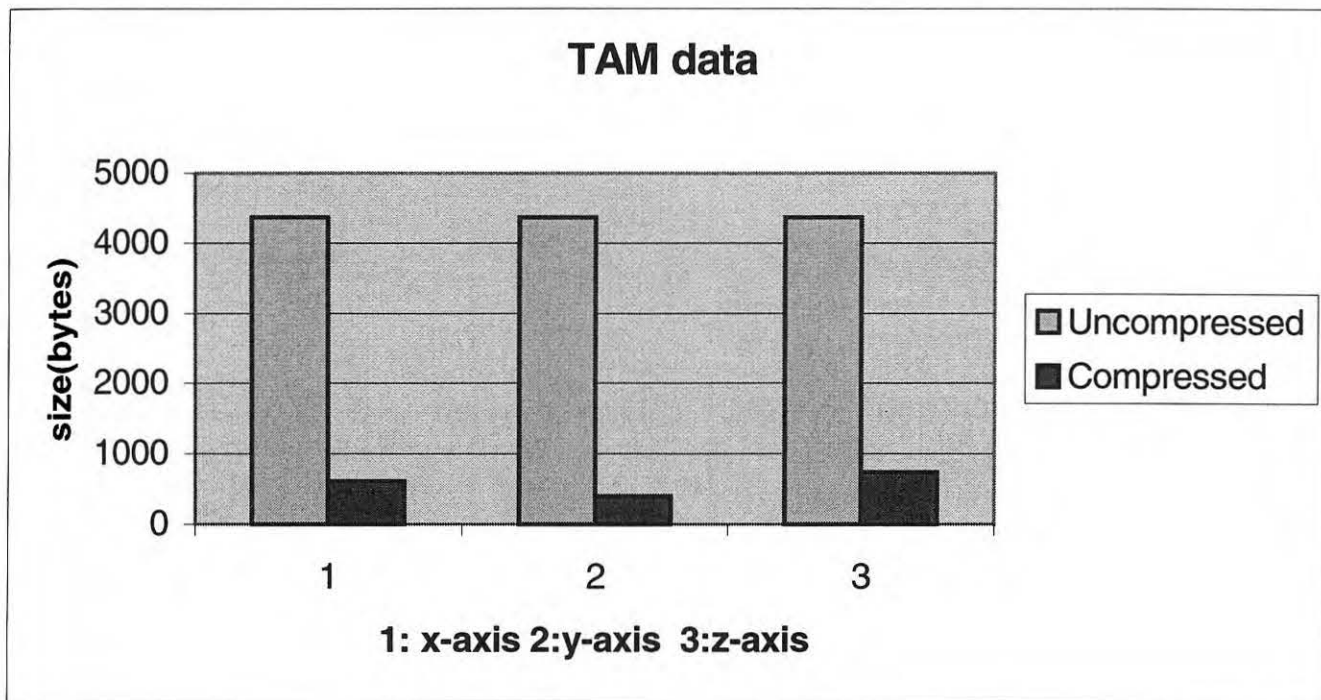


Fig.7. Compression ratio using FTC for Extreme Ultraviolet Explorer three axis magnetometer data

4. Conclusions and Recommendations

For satellite signals having noise levels that do not exceed the value of the least significant bit,

verbatim FTC provides compression ratios from 4:1 to 46:1. Combined with conventional compression methods, FTC can yield an overall compression ratio that exceeds 100:1. Smoothing FTC increases the

overall compression ratio even further and eliminates round-off errors and noise from data.

Satellite telemetry should be restructured. Data should be based on type and compressed on board. For each measurement type, the telemetry stream should include a measurement flag, curve-fit coefficients and the start time for each functional representation

To use the full potential of FTC, the library of functions used for curve fitting should be extensive. In order to compress periodic signals, FTC should be combined with spectral analysis. Smoothing FTC is recommended for noisy signals. The level of smoothing remains to be determined on a case by case basis. Besides compression of audio, video and satellite telemetry signals, other FTC applications should be investigated.

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NOMENCLATURE

- c_l fit coefficients
- P_l^m Legendre polynomial of degree l and order m
- $S(t)$ signal (desired units)
- t time (seconds)
- t_s scaled time (dimensionless)
- x, y, z Cartesian coordinates (desired units)

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