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Simplified Approach to Detect Satellite Maneuvers Using TLE Data and Simplified Perturbation Model Utilizing Orbital Element Variation

Arvind Mukundan and Hsiang-Chen Wang *

Department of Mechanical Engineering and Advanced Institute of Manufacturing with High Tech Innovations, National Chung Cheng University, 168, University Rd., Min Hsiung, Chiayi 62102, Taiwan; d09420003@ccu.edu.tw
* Correspondence: hcwang@ccu.edu.tw

Abstract: This document provides supplementary informations to the article, Simplified approach to detect satellite maneuvers using TLE data and Simplified Perturbation model utilizing orbital elements variation. Section 1 gives an overview of the Pseudocode used in this algorithm while section 2 is gives a detailed description of the case study of TOPEX.

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S1. Pseudo Code

Procedure 1:

INPUT(S): $Ref_{TLE}[]$, $TLE_{file}[n]$ ← TLE.txt,
// calculating the difference in the time values of the reference TLE and TLE(s) in the input text file.
// do while the value of n is not equal to zero
//T_Value is the time array that needs to be propagated
do_while (n != 0)
$TArray_{1[n]}$ ← Difference(T_Value_Ref_TLE, T_Value_TLE_file)
Call SGP4() ← $T\_Array_{1[n]}$
// get position and velocity matrix for each value of $T\_Array_{1[n]}$
Pos_[n x n] ← (Call SGP4() ← $TArray_{1[n]}$)
Vel_[n x n] ← (Call SGP4() ← $TArray_{1[n]}$)
end do_while
for each $TArray_{1[n]}$
// Using Formulae
Calculate ← Keplerian_Elements_1(a, e, m, p, θ , Φ)
end for each
end of Procedure 1

Procedure 2:

INPUT(S): $TLE_{file}[n]$ ← TLE.txt,
for each $Array_{1[n]}$ in $TLE_{file}[n]$
Extract ← Keplerian_Elements_2 (a, e, m, p, θ , Φ)
end for each
end of Procedure 2

Final_Procedure

INPUT(s) ← window length(t'), detection threshold limit (σ'), maneuvering
// Call from Procedure 1 and Procedure 2
// Comparison of the Keplerian_Elements

for(i = 0, i<n, i++)
$comp_1 \leftarrow$ (Keplerian_Elements_2 - Keplerian_Elements_1)
error_difference_$\triangle(comp_1)$
if(error_difference_$\triangle$ > σ' && t′ satisfies)
maneuvering $\leftarrow$ true
else
maneuvering $\leftarrow$ false
end else-if
end for
OUTPUT $\leftarrow$ Plots(position, time)
End Final_Procedure
End of Algorithm

S2. Implementation and Result

This study focused on two satellite missions: TOPEX (SSN# 22076), and Envisat (SSN# 27386). Both these satellites have the TLE sets in extremely quality, and their maneuver histories are obtainable. The TLEs for both were procured from the CelesTrak website. The maneuver history for both satellites were obtained from the International Laser Ranging Service website [1] [2]. The TLE datasets and the maneuver history of both are unclassified resources and are accessible for everyone. Although the TLE data are available for almost 45,920 satellites, including decayed and in-orbit satellites, such as SES 1, NOAA 19, and GOES 13, TOPEX and Envisat were specifically chosen to represent an example of simplest fine control, in-plane maneuvers, most complex orbit control, and out-of-plane maneuvers.

S2.1. TOPEX

TOPEX, also known as Poseidon, was launched on the 10^{th} of August 1992 as a collective initiative by NASA and CNES. The mission of TOPEX was to measure the ocean surface topography [3]. It was also the first major oceanographic research satellite, which bolstered oceanography by contributing vital information that was unmanageable to procure in the past. However, normal satellite operations ended in January 2006 due to a minor malfunction. The TLE data recovered for the case study of TOPEX in this research cover a period of three years, i.e., from 1993 to 1995. The adjacent time between each TLE averages approximately 24 h, i.e., one TLE was chosen per day to study the orbital parameters. The orbit of TOPEX has an average mean motion of approximately 13 revolutions per day, with an orbit period of 112 min, an average semimajor axis at 7711 km, and an inclination of 66°. Figure S1 depicts the maneuver history, which is represented by vertical light green lines. TOPEX demonstrates the maneuver detection algorithm with a smooth and straightforward case of six fine control maneuvers with a magnitude in mm/s. A total of six maneuvers performed over a period of 3 years has an average change in velocity magnitude of 4–5 mm/s [4].

This study's approach was to demonstrate initially a baseline case, which was manipulated by changing the two parameters; window length and detection threshold, and draw an analogy between the sensitivity of the maneuver detection algorithm and the two parameters, namely, maneuver detection limit and window length between maneuvers. The baseline did not manifest a perfect scenario of maneuver detection. Nevertheless, it enabled us to compare the relative performance of four different cases by increasing and decreasing the maneuver detection limits and window length. Once the baseline case was established, four cases were compared with it. Two cases were formulated by increasing and decreasing the maneuver detection limit, whereas the other two cases were formulated by increasing and decreasing the window length. The trial-and-error technique was used through various trials before finalizing a baseline case for TOPEX and Envisat. The values of the two parameters used in the baseline case were the reference values, which were named as "1-sigma". By manipulating the "1-sigma" values, we compared the relative performance of the algorithm.

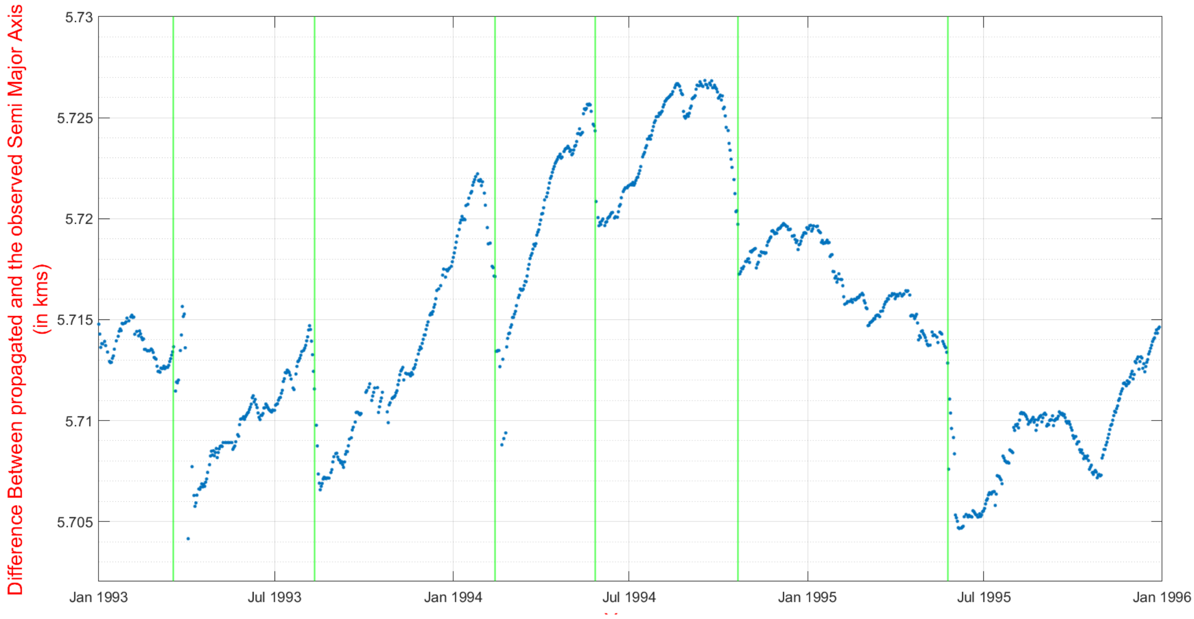

Figure S1. Maneuver history of TOPEX, Vertical green line represents the maneuvers.

S2.1.1. Baseline Case: perfect detection and no false detection

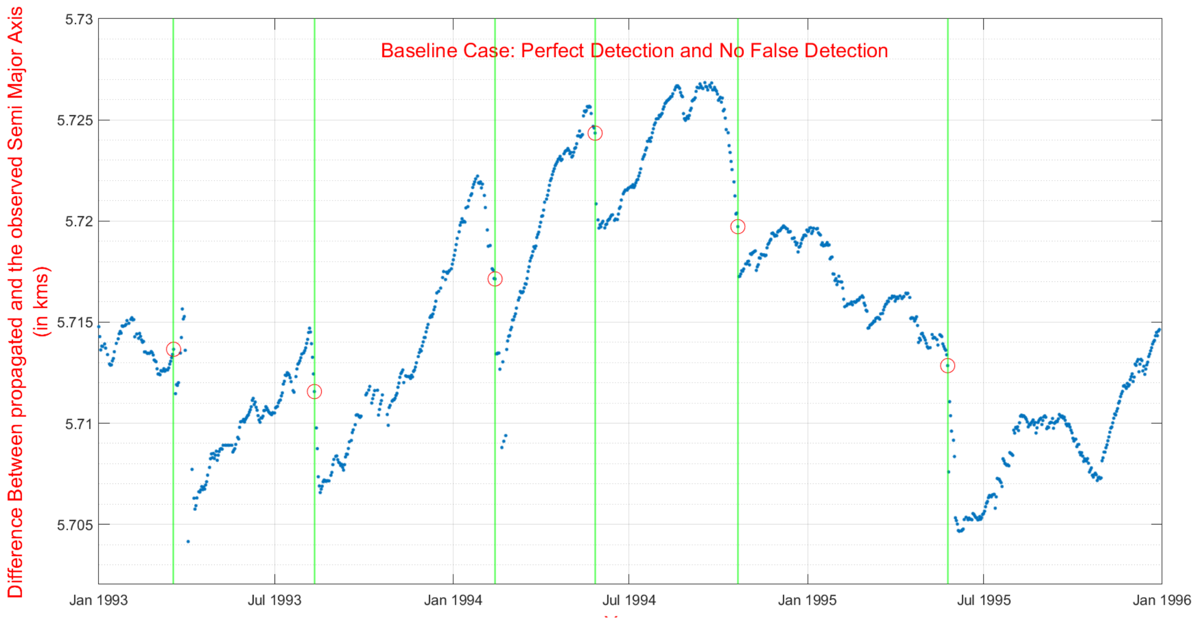

Figure S2. Baseline Case, Vertical green line represents the maneuvers and the red circle represents potential maneuvers detected from this method.

The baseline parameter is characterized by perfect detection of all the maneuvers with no false maneuver detection. In the case study of TOPEX, the baseline parameter was calibrated with a window span of 40 data points between each maneuver detection (approximately 40 days in time units) and when a threshold of detection of 1-sigma is used. Figure S2 depicts the resulting maneuver detected as red circles. In this case, all the six maneuvers within a period of 3 years were detected perfectly without false detection.

S2.1.2. Case 1: Maneuver detection threshold magnified to 2-sigma relative to baseline 1-sigma Case

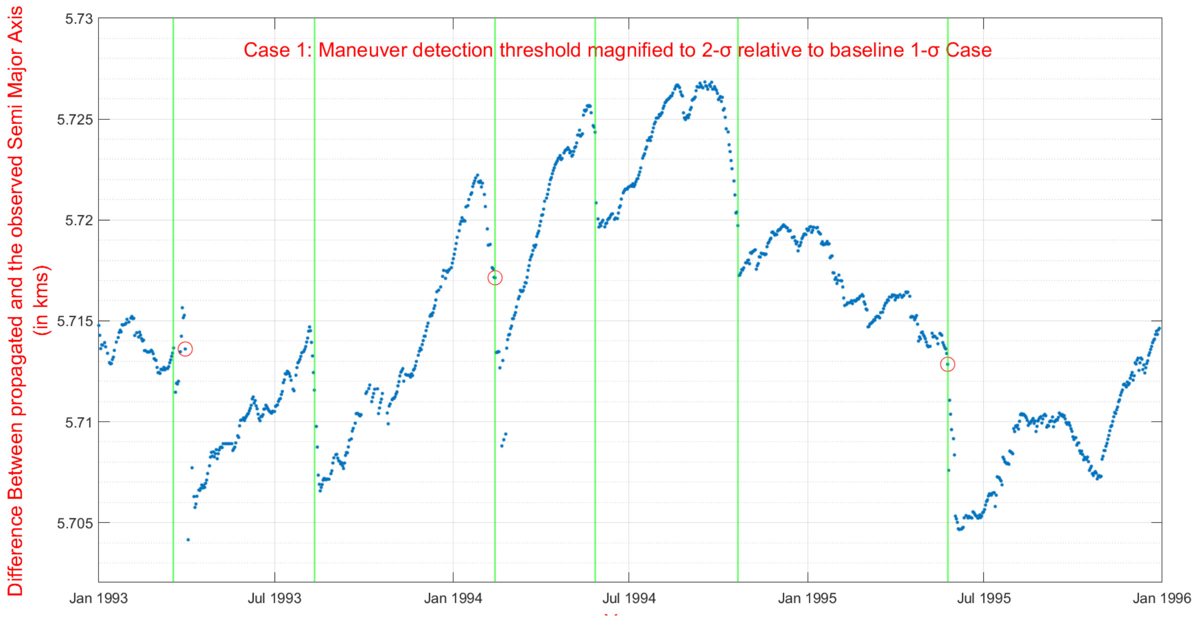

Figure S3. Case 1: Increase in maneuver detection threshold, Vertical green line represents the maneuvers and the red circle represents potential maneuvers detected from this method.

Figure S3 demonstrates the consequence of increasing the maneuver detection parameter to 2-sigma from 1-sigma. The effect of this increase is that a total of four of the six known maneuvers were missed, whereas one false detection was present. This effect was expected because an increase in the detection threshold leads to less maneuver detection. The maneuver detection threshold when raised by a large magnitude can result in no maneuver detection. The detection limit threshold is directly related to the ΔV. When the ΔV of a satellite is less then the detection limit threshold should also be reduced.

S2.1.3. Case 2: Maneuver detection threshold reduced to 0.5-sigma relative to baseline 1-sigma Case

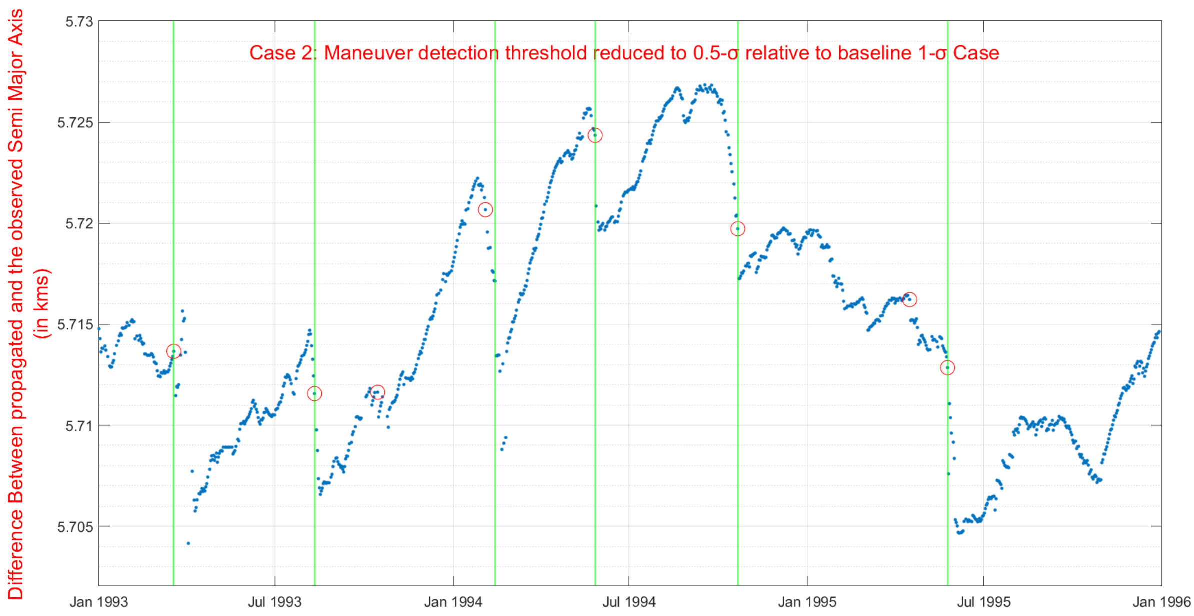

Figure S4. Case 2: Decrease in maneuver detection threshold, Vertical green line represents the maneuvers and the red circle represents potential maneuvers detected from this method.

Figure S4 demonstrates the consequence of decreasing the maneuver detection parameter to 0.5-sigma from 1-sigma, which resulted in the algorithm detecting five of the six maneuvers but also three new false maneuvers. This result was also expected because decreasing the maneuver detection threshold affects the amount of false detection. Cases 1 and 2 depict a perfect example of the sensitivity between maneuver detection threshold and maneuver detection performance.

S2.1.4. Case 3: Window length decreased by a factor of three relative to baseline case with detection limit 0.5-sigma

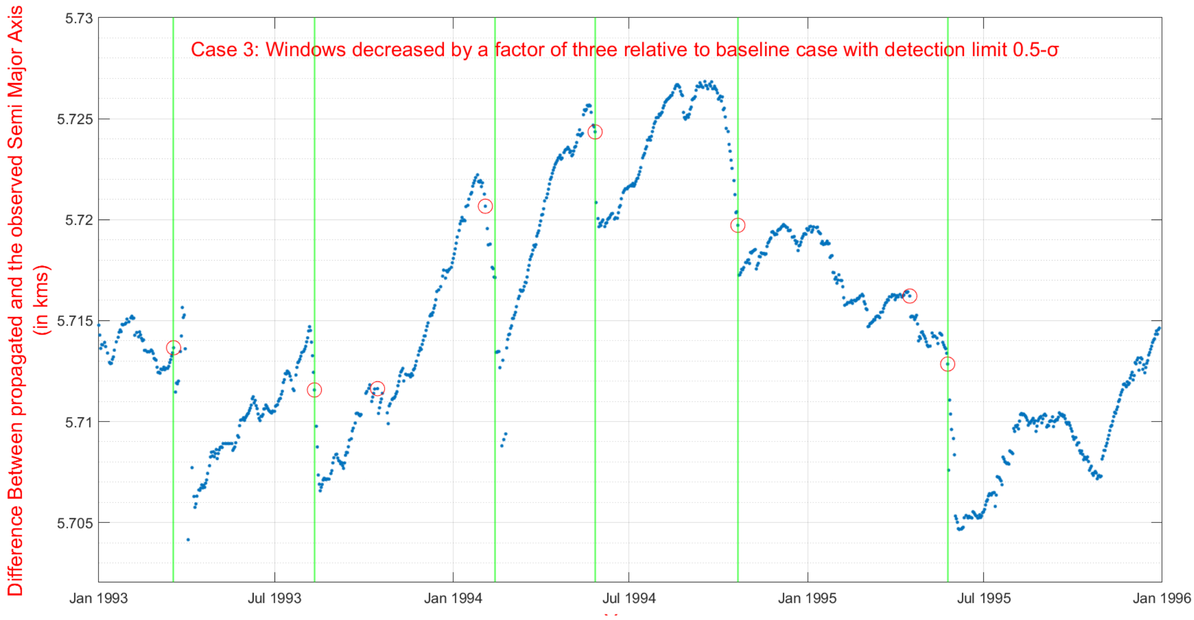

Figure S5. Case 3: Window decreased by a factor of three relative to baseline case with detection limit 0.5-sigma, Vertical green line represents the maneuvers and the red circle represents potential maneuvers detected from this method.

Figure S5 depicts the consequence of reducing the window length by a factor of 3, with reference to the baseline case from 40 data points (approximately 40 days in time units) to 15 data points (approximately 15 days in time units). Given this reduction, one of the six maneuvers, which were observed in the first case, was undetected, whereas four new false maneuvers were detected due to noisy data. This result is due to a decrease in the window length pushing that single undetected case outside of the 10-day detection threshold.

S2.1.5. Case 4: Window increased by a factor of four relative to baseline case with detection limit 0.5-sigma

Figure S6 depicts the consequence of increasing the window length by a factor of 4, with reference to the baseline case from 40 data points each (approximately 40 days in time units) to 160 data points (approximately 160 days in time units). The result of decreasing the window length shows that the only four out of the six maneuvers that were observed in the first case are missing, whereas one new false maneuver was detected, resulting from the noisier data.

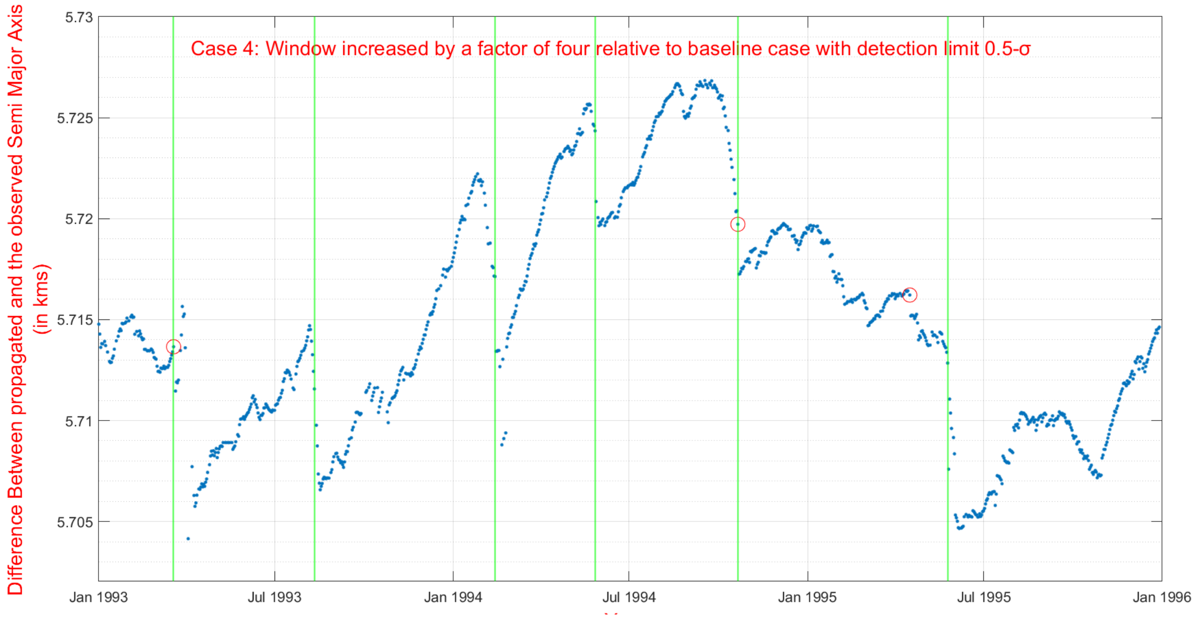

Figure S6. Case 4: Window increased by a factor of four relative to baseline case with detection limit 0.5-sigma, Vertical green line represents the maneuvers and the red circle represents potential maneuvers detected from this method.

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