# Preliminary algorithms for simulating and analysing microwave link data from ACES

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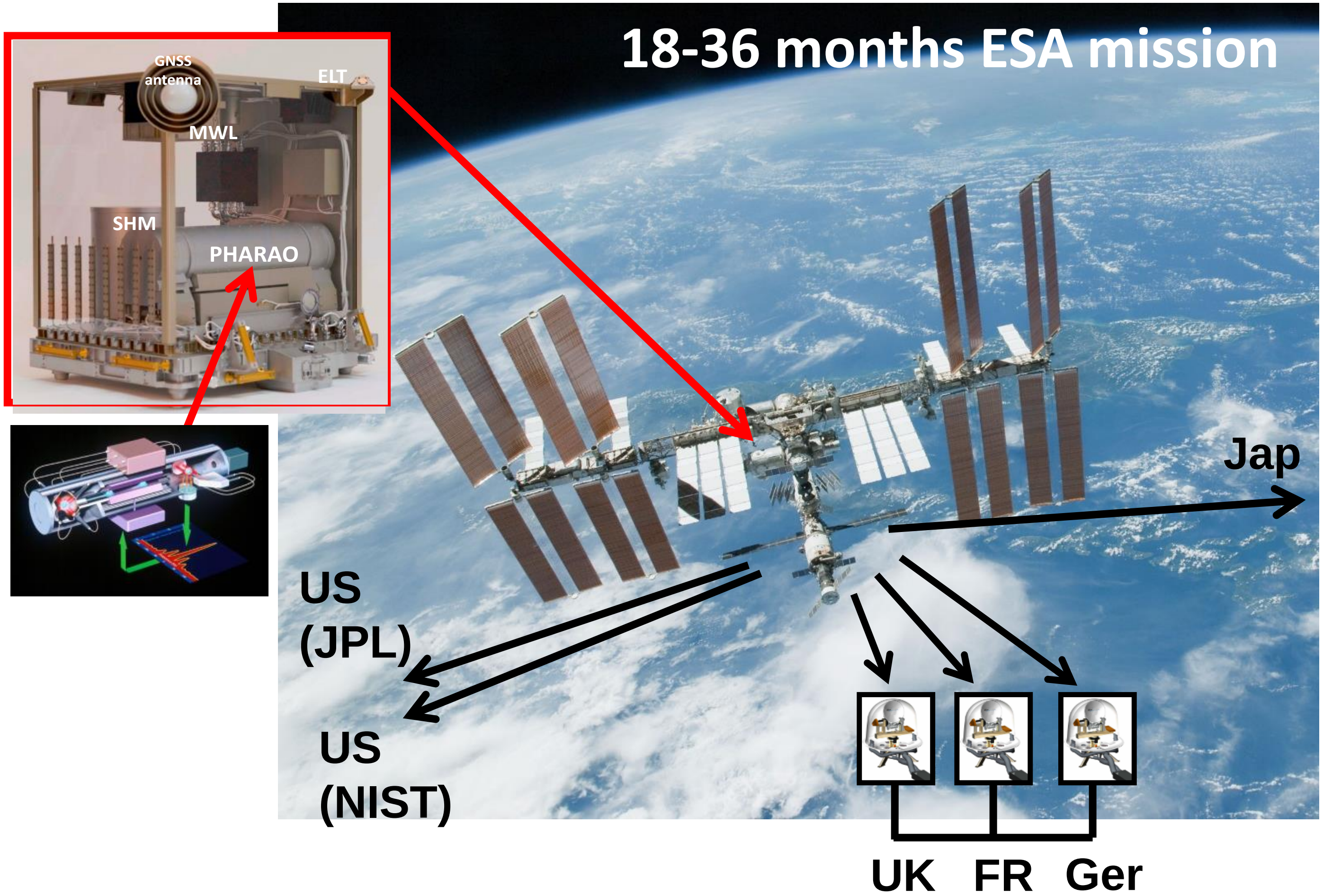
# Introduction (ACES)




ACES will test

-Space clocks and ground optical clocks

-MicroWave Link (MWL)

-Tests of GR

# ACES ground station locations

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# NPL inputs for ACES

- Optical clocks
  - $Yb^+$ ion optical clock
  - Sr lattice clock

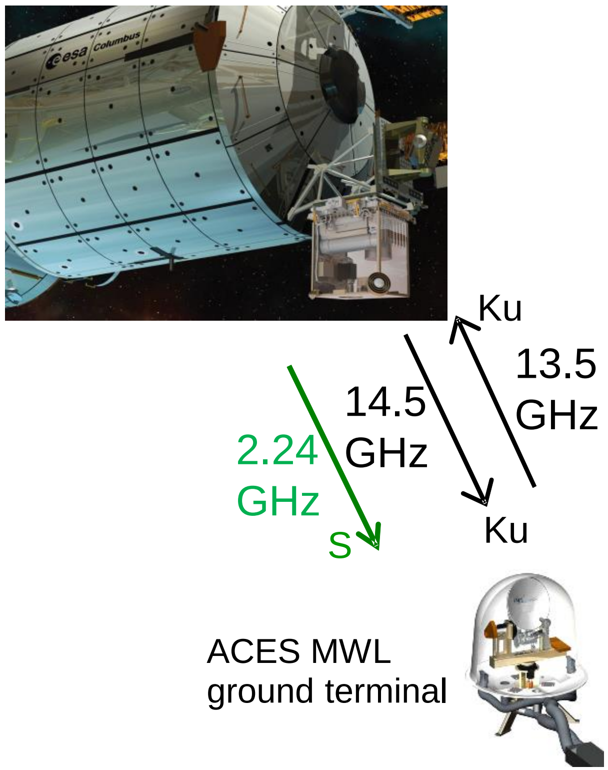
- Caesium fountains
  - NPL-CsF2
  - NPL-CsF3

- Frequency combs

- UTC(NPL)

- Optical fibre link connecting NPL to SYRTE-PTB

# Project objectives




Develop a framework of algorithms for simulating and analysing ACES microwave link code-phase data.

# Analysis of ACES microwave link data

Objectives

- A 1–year ‘Fast-track’ R&D project funded by the UK Space Agency and the UK National Measurement System to investigate analysis methods for exploiting MWL data.
- Limited what can be achieved in 1–year – aim is to do research into the MWL system and physical effects and to develop prototype algorithms.
- We are not implementing a fully operational data processing software which would need a lot more time and effort.

# Algorithms software development

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| Simulation | Analysis |
| --- | --- |
| Models ISS and ground station relative motion, taking into account atmospheric and relativistic effects, to simulate received signal code-phase. This is then converted to TimeTech output cycle counts. | Takes in the TimeTech output cycle counts and reconstructs physical parameters of interest such as the beat note frequency and the pseudo-Time-Of-Flight (TOF + time dilation). |
| Main developer: Hannah Collingwood | Main developer: Kathryn Burrows |
| Coded in Python. | Coded in Matlab. |

# Some physical and MWL system processes

ISS orbit - keplerian orbit implemented, considered only a circular orbit so far.

Motion of the ground station – constant angular rotation of a spherical Earth.

Microwave signal code and carrier-phase information – only code-phase tested

Signal times-of-flight – mainly tested for downlink signals

Relativistic effects – only considered effects of relativistic motion and gravitational potential, not signal propagation in curved spacetime, etc

Atmospheric effects

Ionosphere – only considered fixed constant ionosphere so far.

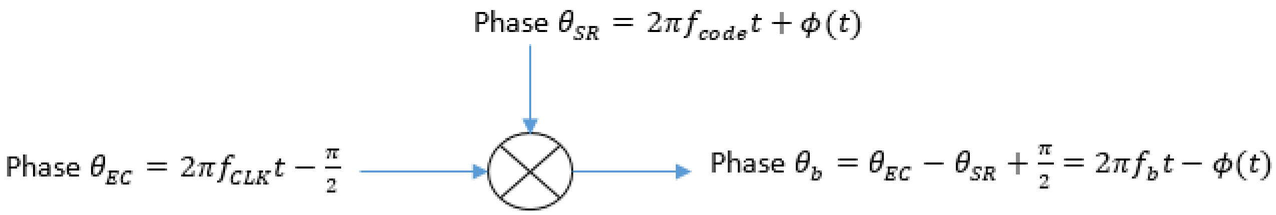
Troposphere – not considered in detail.

Signal processing according to TimeTech measurement principle – code-phase only

Equipment calibrations and corrections – not considered.

Clock noise – not considered.

# MWL signal processing




$$\frac{1}{f_{CLK}} = \frac{1}{100\ 195\ 312.5\ \mathrm{Hz}} = 9.9805\ \text{ns.}$$

Received code has a frequency of 100 MHz + Doppler shift + other effects of interest.

Code beatnote frequency is nominally 195.3125 KHz, if received signal is at 100 MHz.

Mixer arrangement is used to improve the measurement resolution of the code phase to approx. 19.5 ps.

# Graphical user interfaces

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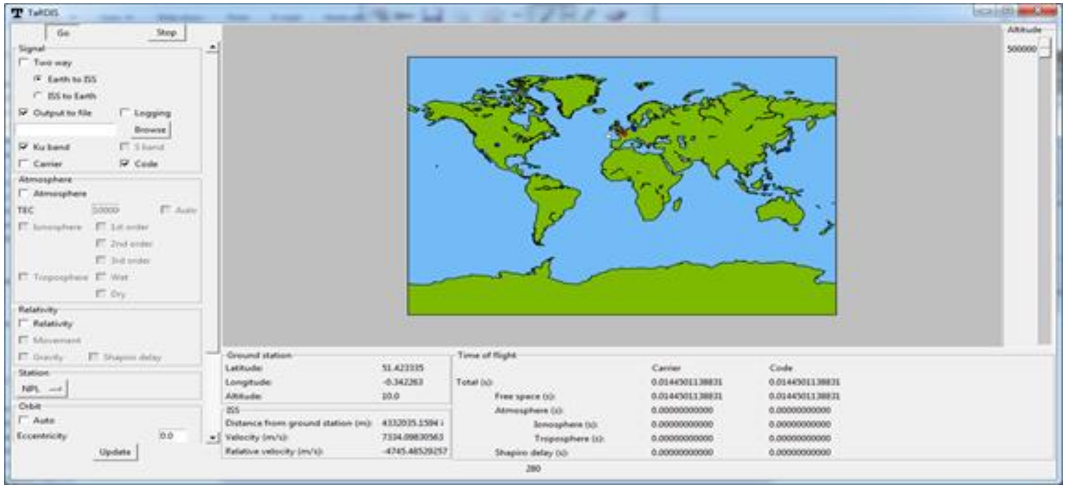
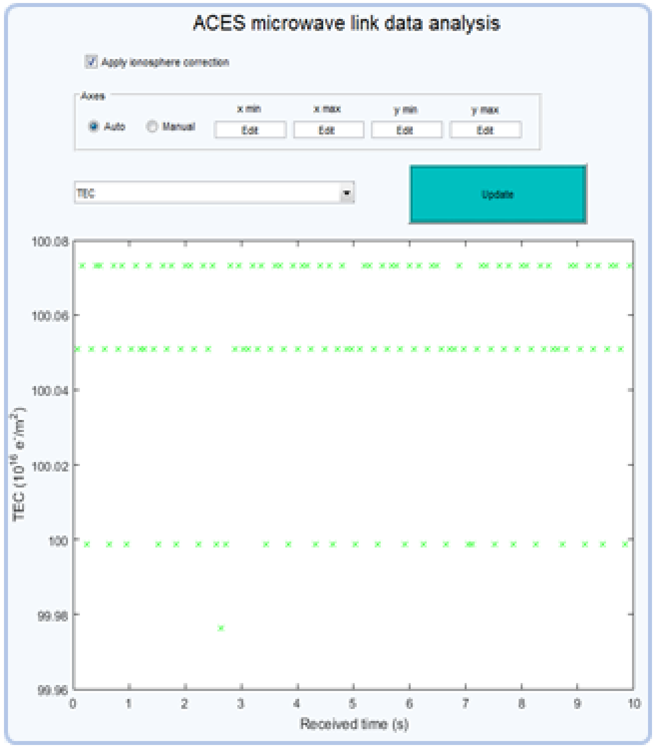
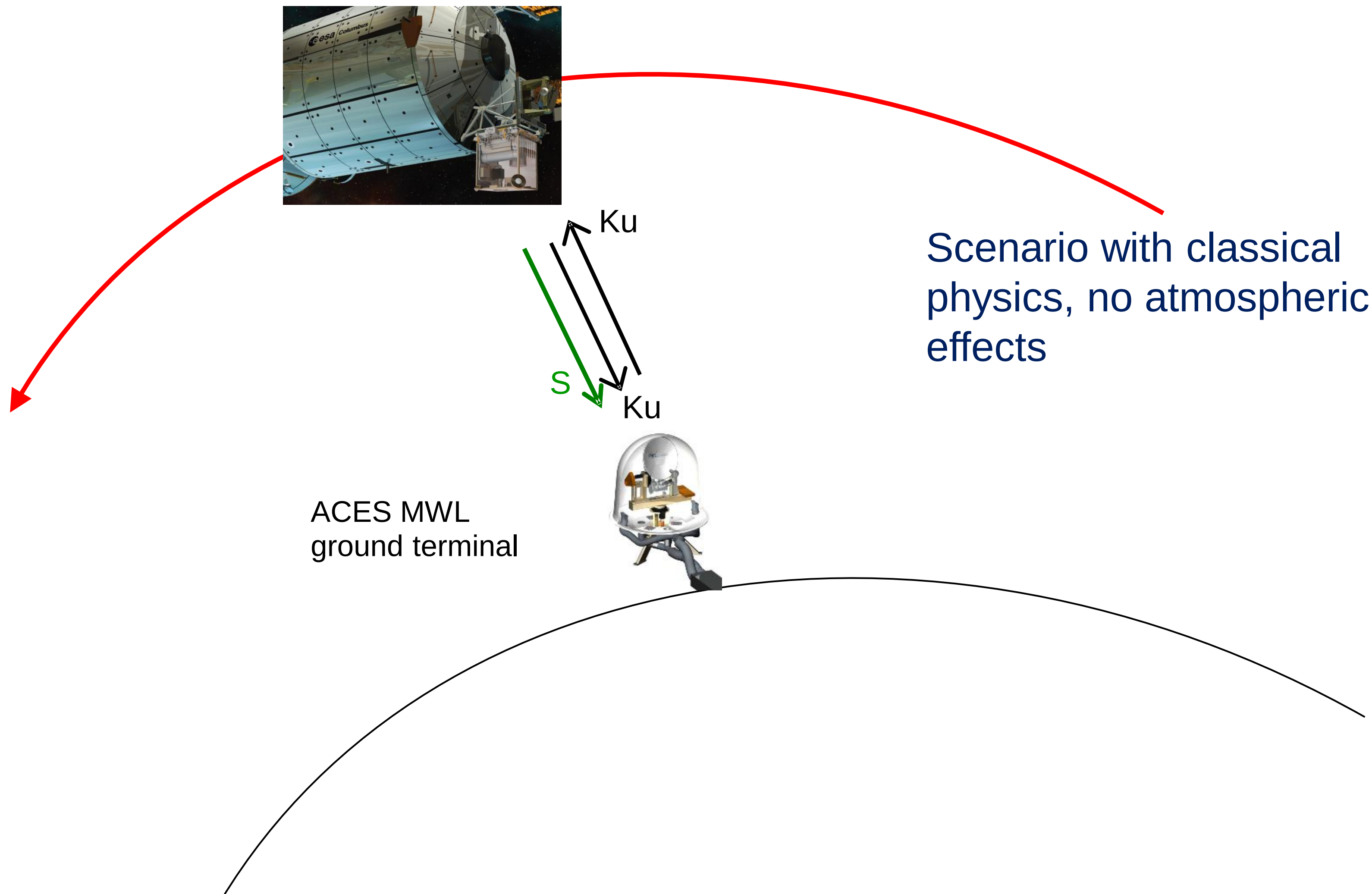



Simulator



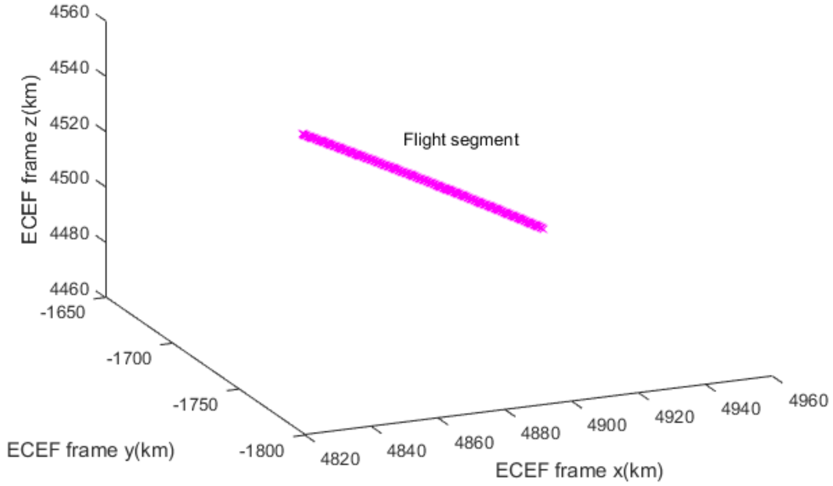

Analysis

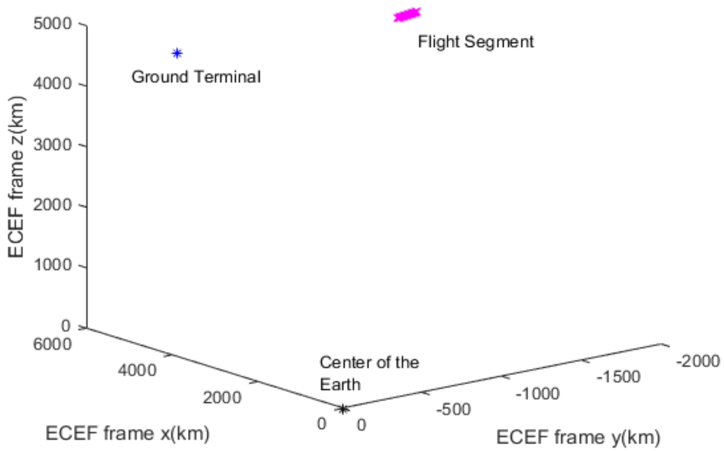
# Test scenario 1: Classical physics




Scenario with classical physics, no atmospheric effects

# Test scenario1: Classical physics - Flight segment positional data

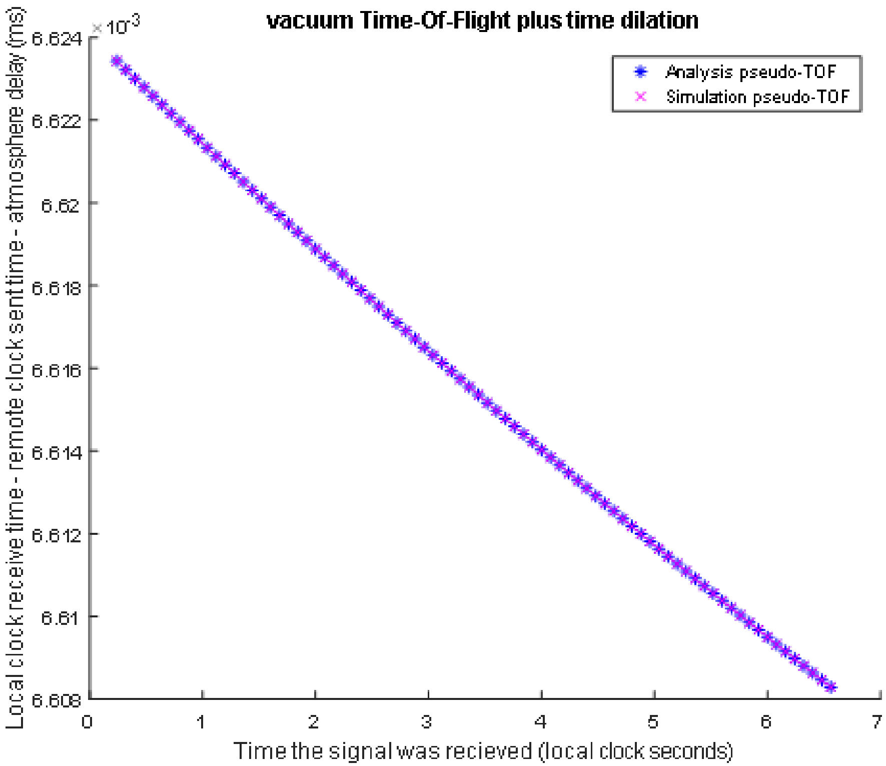



A plot of the simulated position of the Flight segment in ECEF frame over 7 s.

A plot of the simulated positions of the Flight segment in ECEF frame, the NPL GT and the centre of the Earth over 7 s.

# Test scenario 1: Classical physics – downlink signal

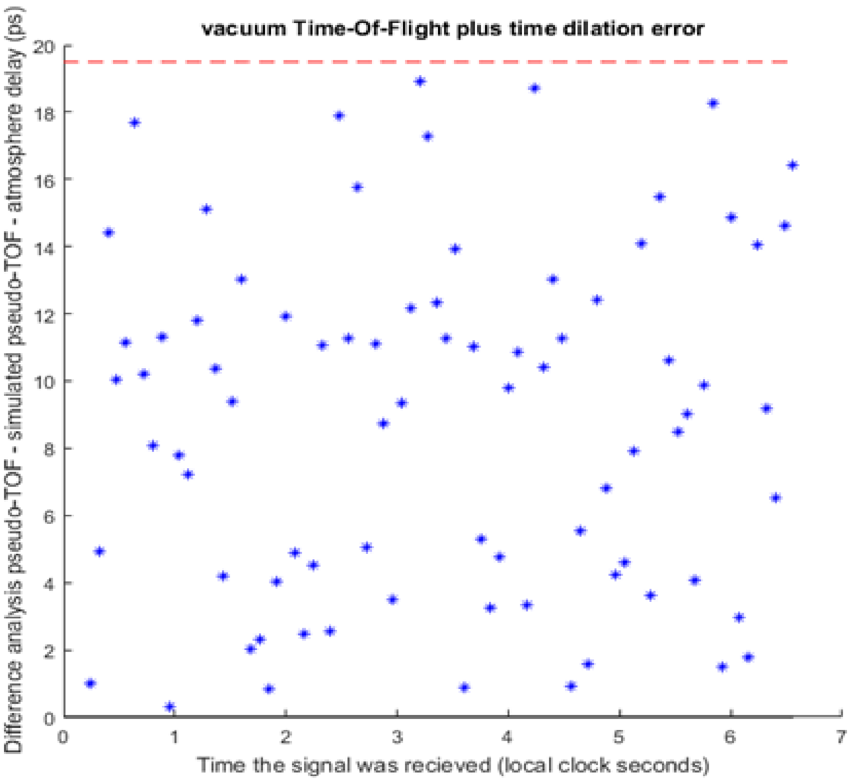



Classical physics scenario

The Time-Of-Flight (TOF) of the signals is shown according to the simulator and the analysis outputs.

As classical physics is considered, there is no time-dilation between the space and ground clocks.

# Test scenario 1: Classical physics – downlink signal

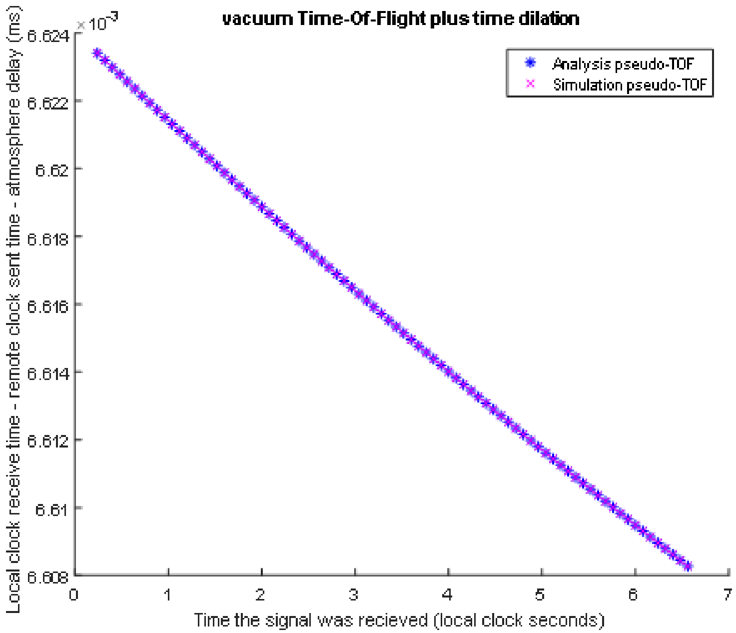


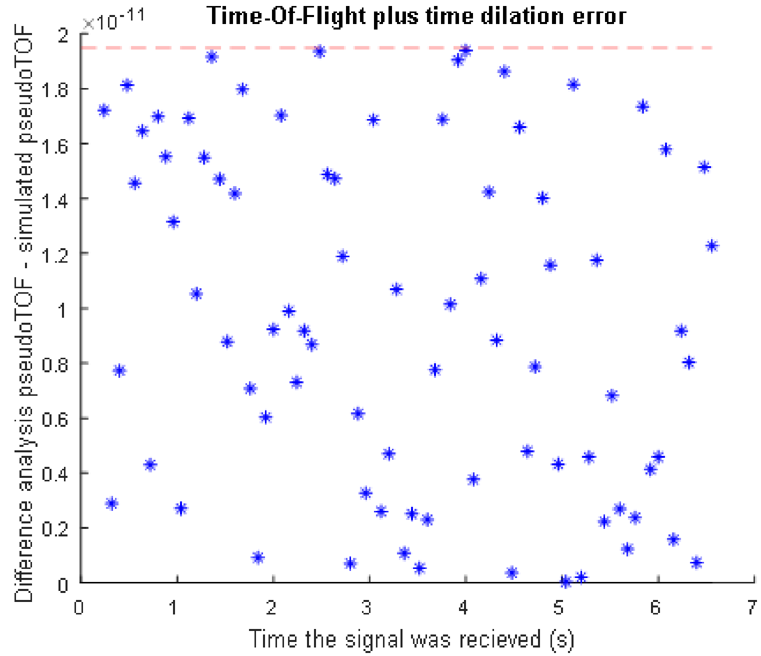

Classical physics scenario

Agreement between the analysis code and the simulated values to within 19.5 ps (3 sf) is used to verify that the simulation code is internally consistent.

The 19.5 ps level shown arises due to measurement uncertainty and is the best that can be achieved using an individual measurement of the code-phase.

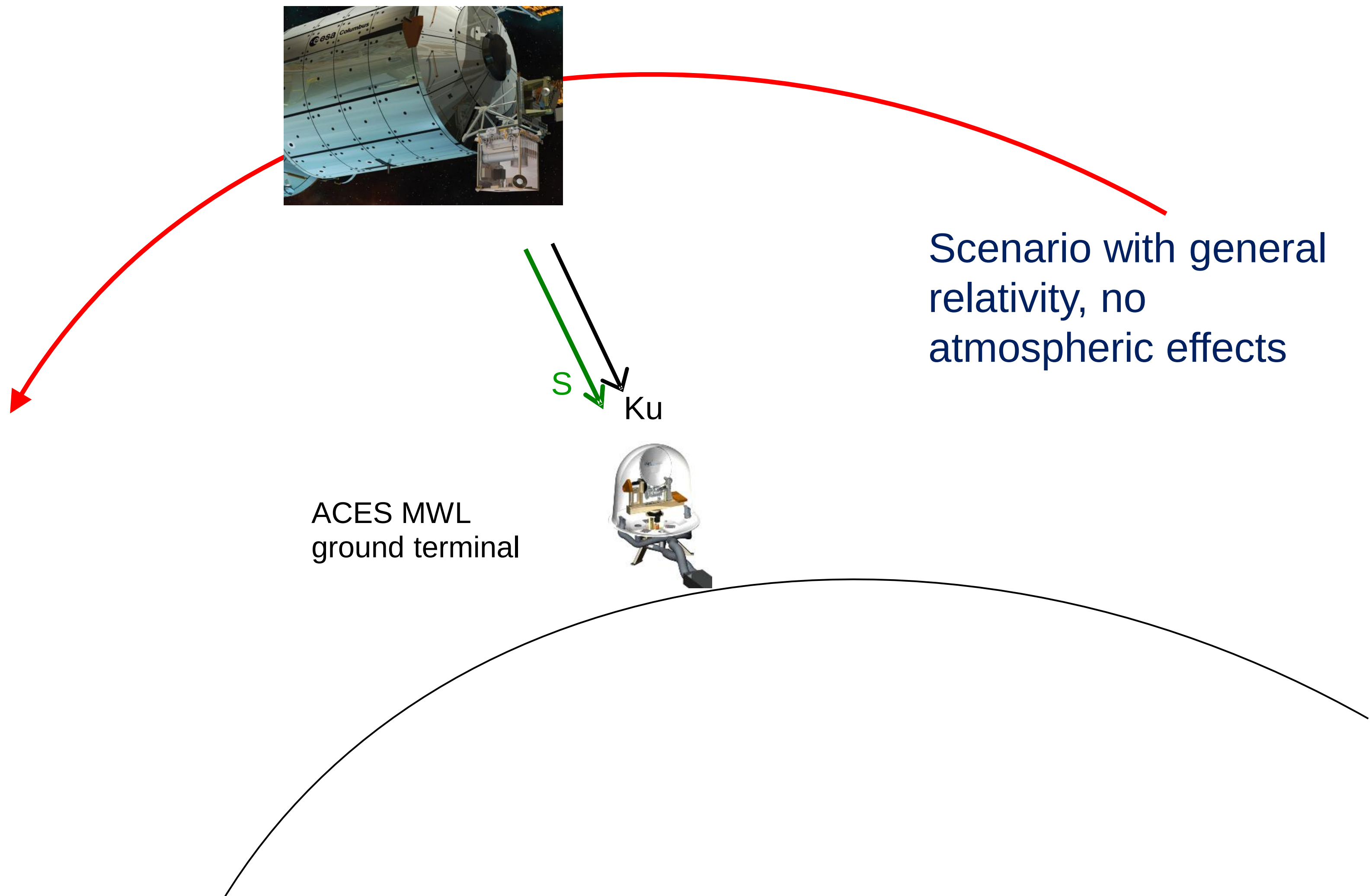
# Test scenario 1: Classical physics - uplink signal



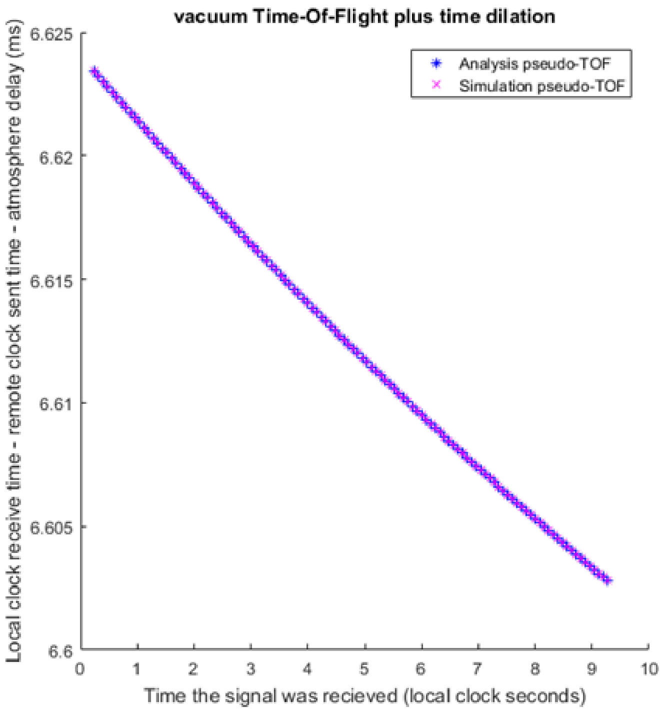

- Agreement found between simulation and analysis outputs to within 19.5 ps.
- The 19.5 ps level shown arises due to measurement resolution and is the best that can be achieved using an individual code-phase measurement.

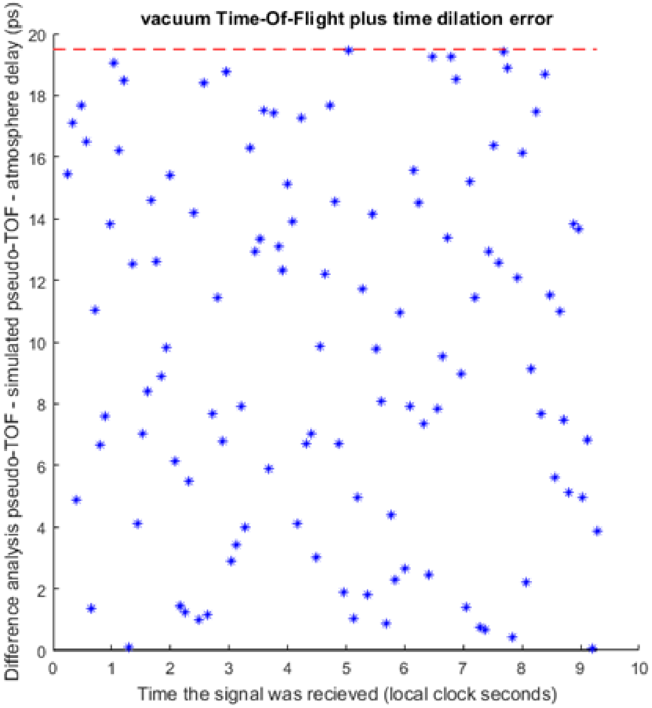
# Test scenario 2: General relativity




Scenario with general relativity, no atmospheric effects

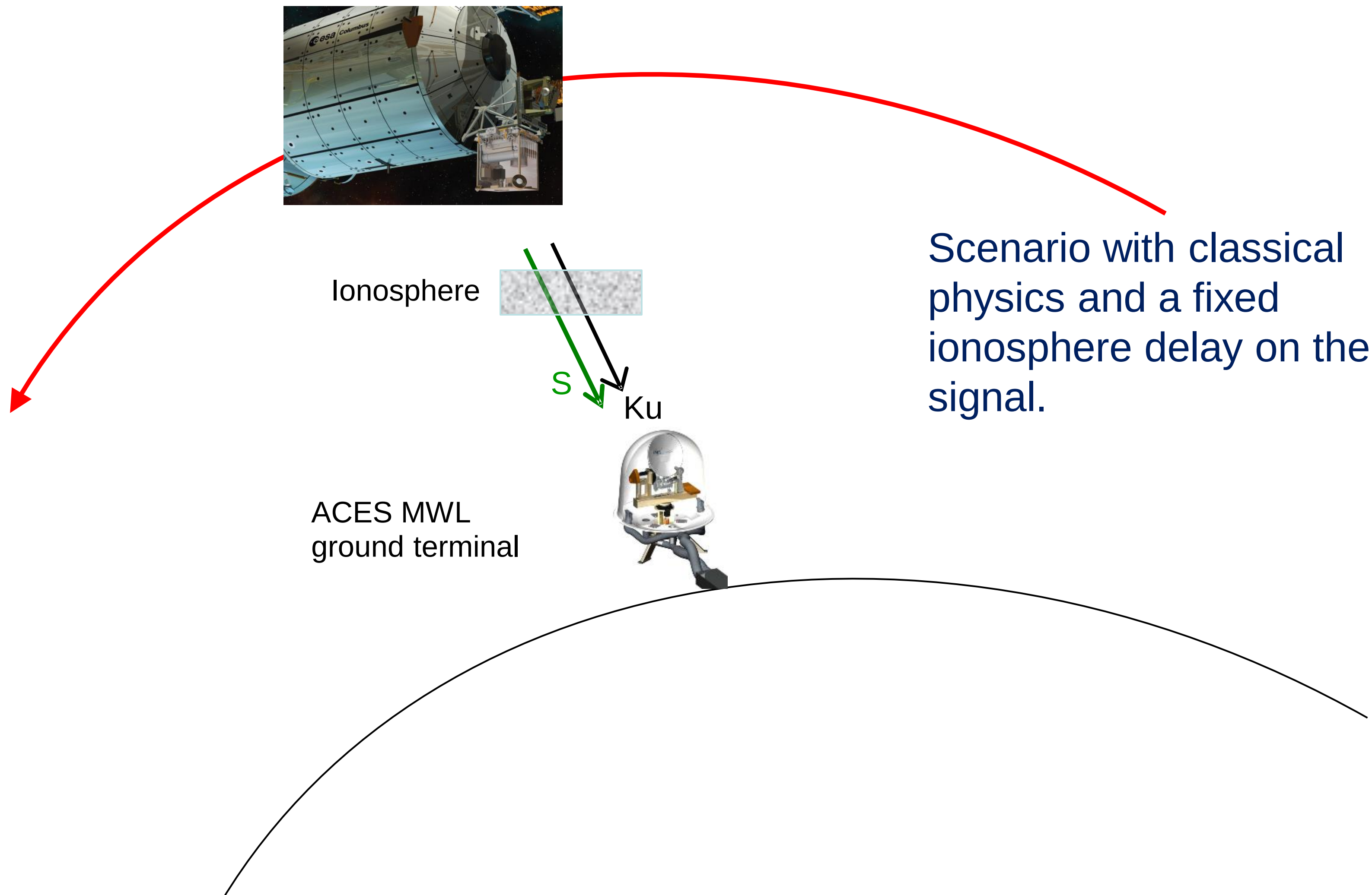
# Test scenario 2: General relativity – downlink signal




- Agreement found between simulation and analysis outputs to within 19.5 ps.
- This is particularly challenging in the general relativistic case where there are clock offsets between the ground terminal and the flight segment clocks.

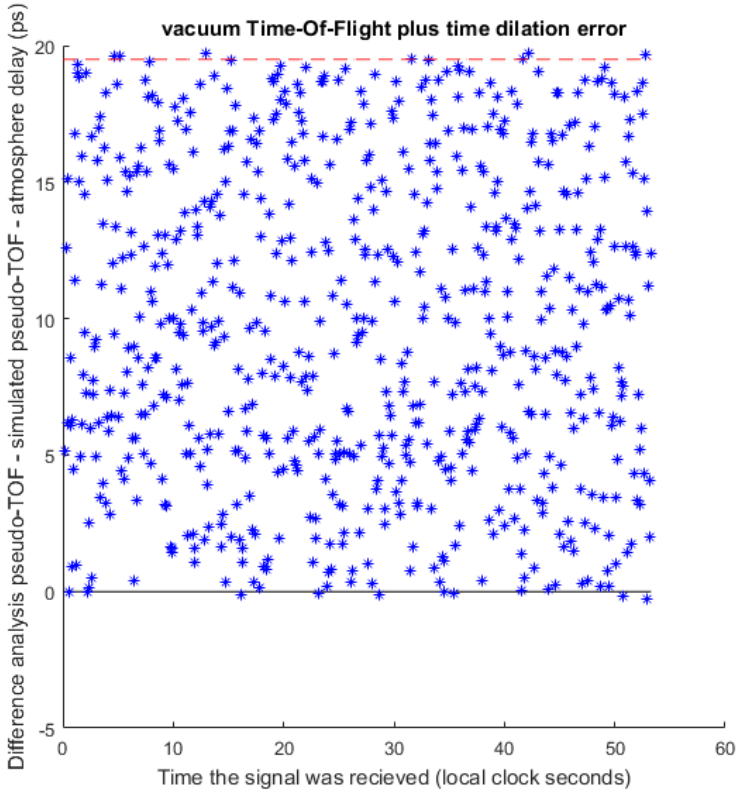
# Test scenario 3: Classical physics with a fixed ionosphere delay



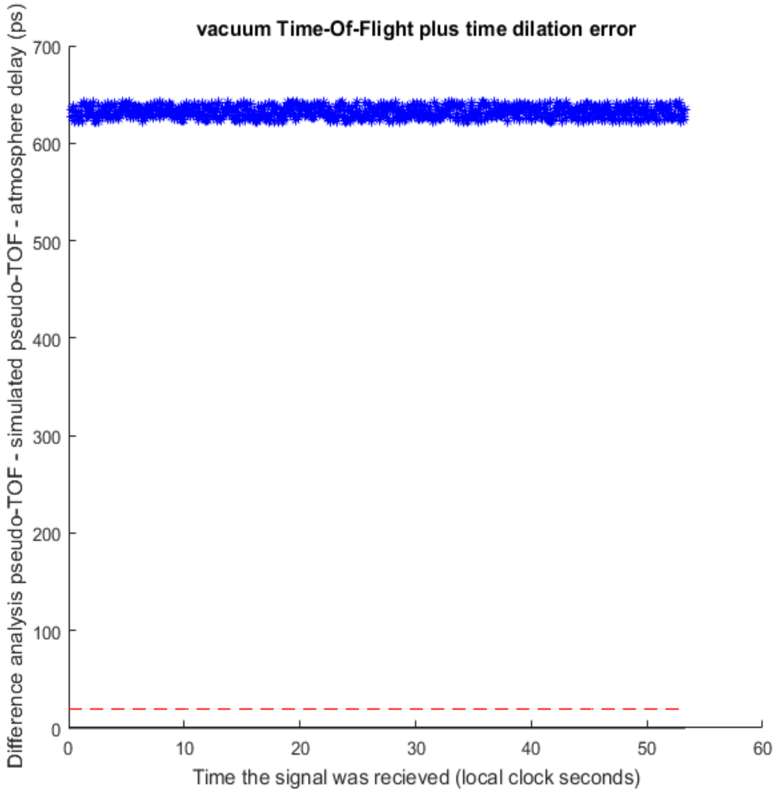

Scenario with classical physics and a fixed ionosphere delay on the signal.

# Test scenario 3: Classical physics with a fixed ionosphere delay

Uncorrected ionosphere delay within the analysis software




Corrected ionosphere delay within the analysis software

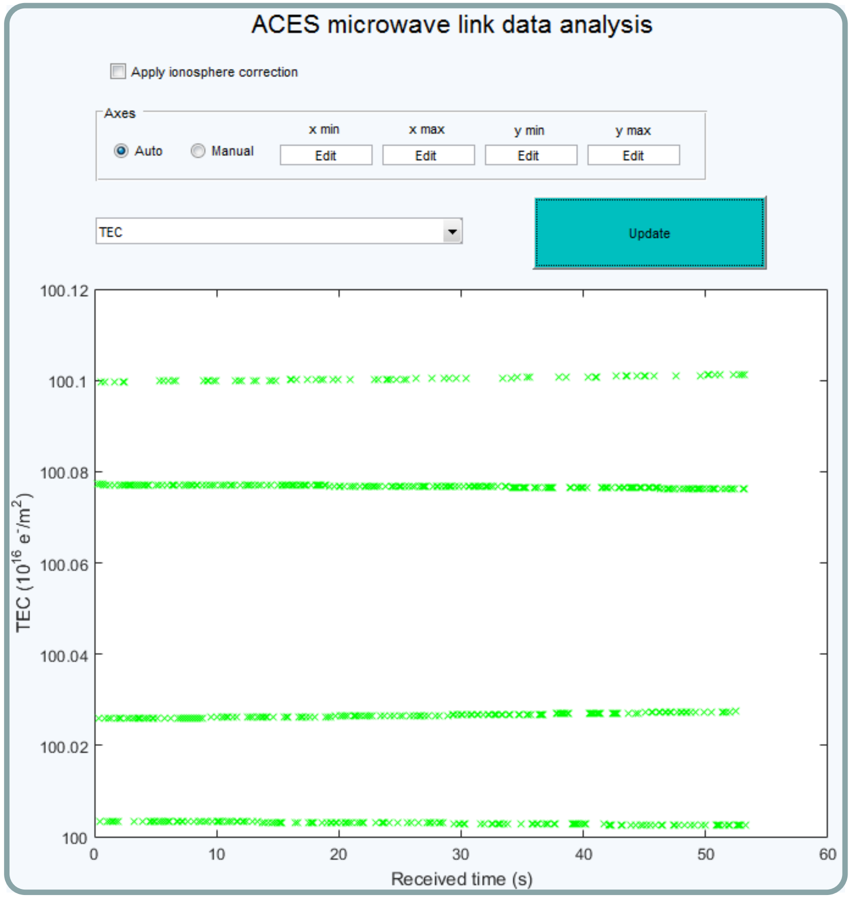



Classical physics scenario with a fixed ionosphere delay (of 100 TEC units)

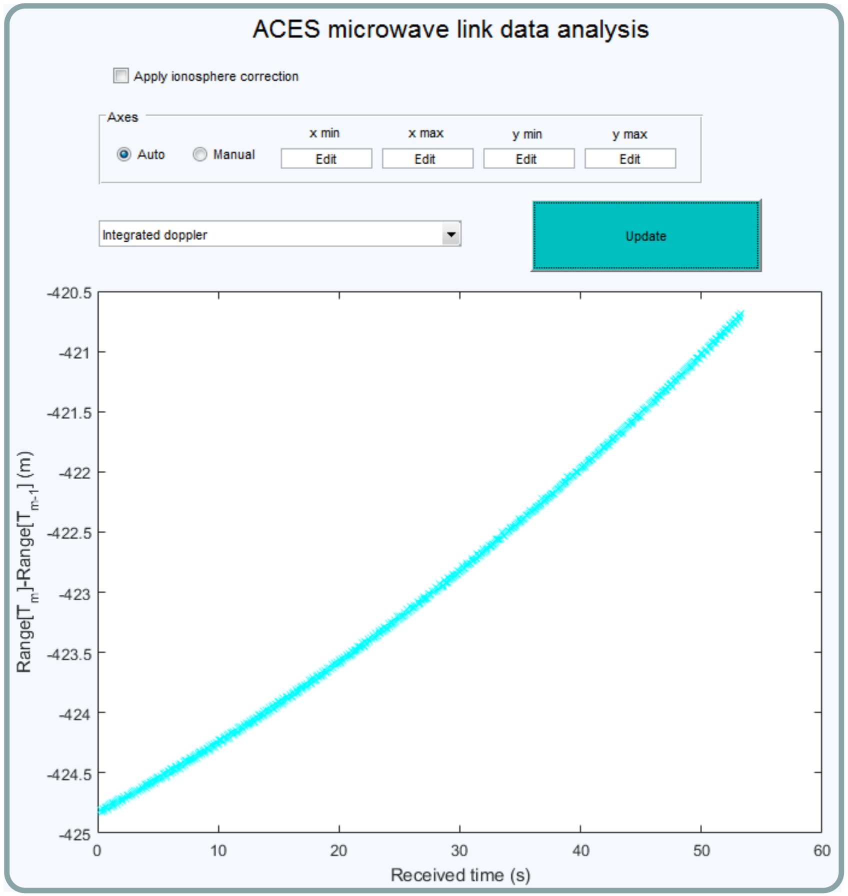
General agreement to within 19.5 ps as expected, although not always.

# Test scenario 3: Classical physics with a fixed ionosphere delay

Total electron content

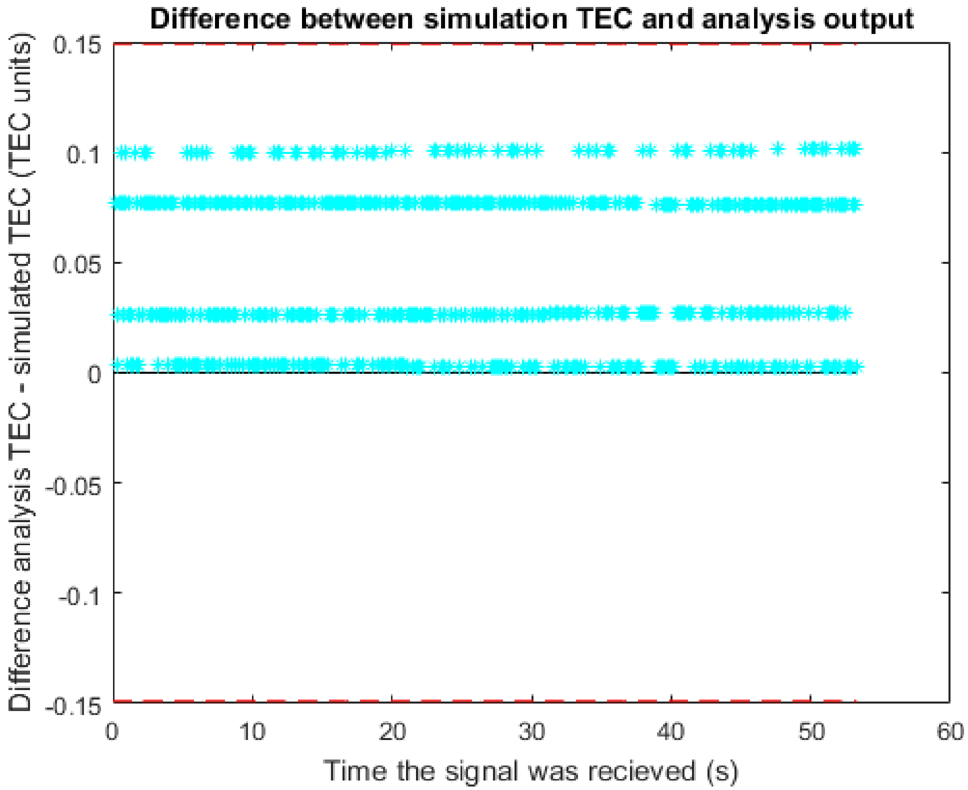



Integrated Doppler range difference




Classical physics scenario with a fixed ionosphere delay (of 100 TEC units)

# Test scenario 3: Classical physics with a fixed ionosphere delay




The analysis code is able to reconstruct the simulated total electron content of the ionosphere to within measurement uncertainty values of 0.15 TEC units.

Classical physics scenario with a fixed ionosphere delay (of 100 TEC units)

# Potential future work

1. Develop algorithms for two-way time/frequency transfer.

2. More detailed consideration of ionospheric/tropospheric effects.

3. Consider carrier-phase analysis.

4. Potential tests involving NPL analysis of simulated data from Paris Observatory.

Applying for more follow-on funding from the UK Space Agency.

# Summary

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- A 1-year project to develop preliminary algorithms.
- A framework of algorithms has considered the code phase and mainly downlink signals.
- Initial results for classical physics, general relativity and ionospheric effects show some consistency, but further testing and development are required.
- The framework could be extended to include two-way processing and carrier-phase analysis, and used to analyse Paris Observatory simulated data.
- In  process of applying for more UK Space Agency funding.

Part funded UK space agency NSTP2 fast track project

Department for Business, Energy & Industrial Strategy

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# NPL interpretation of emitted, received and beat note signal code-phases in MWL

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