# Galileo I/NAV Improvement

D/NAV

UNOOSA ICG Annual Meeting – October 2022

# Outline

- **I/NAV Improvement – User Benefits**
- I/NAV Improvement – Technical Content
  - Reduced Clock and Ephemeris Data
  - Reed Solomon coded Clock and Ephemeris Data
  - Secondary Synchronization Pattern
- User Exploitation and Performance
- Deployment Status

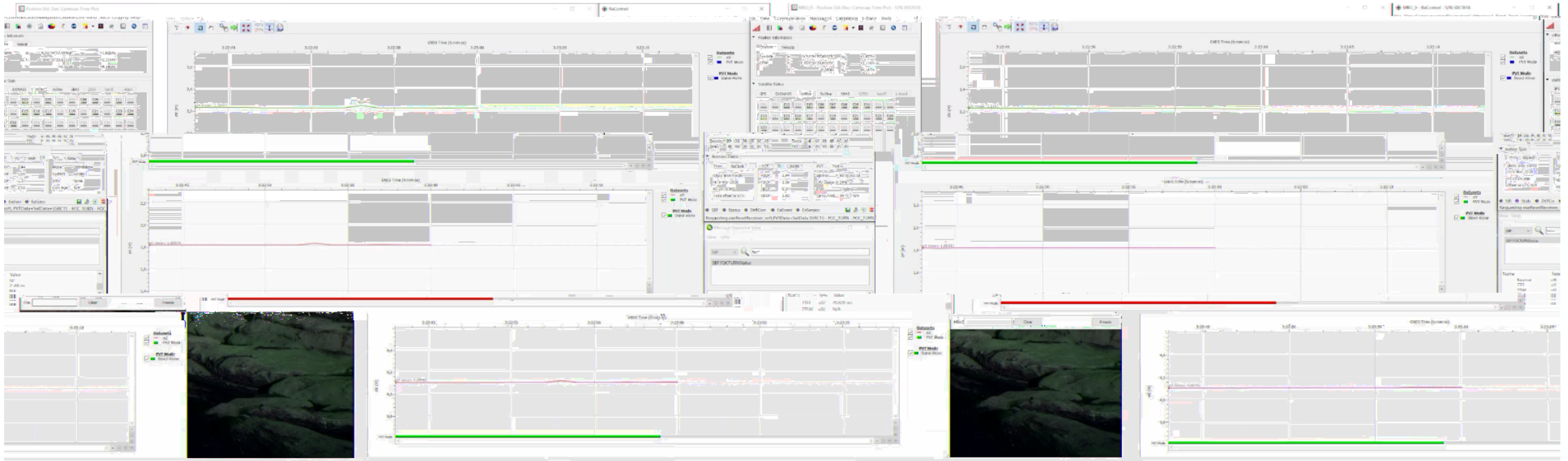
# I/NAV Improvement - User Benefit

Position error (x,y,z) with I/NAV Legacy

Step 1: Rx Reset

Position error (x,y,x) with I/NAV Improvements

Step 1: Rx Reset



# Outline

- I/NAV Improvement – User Benefits
- **I/NAV Improvement – Technical Content**
    - Reduced Clock and Ephemeris Data
    - Reed Solomon coded Clock and Ephemeris Data
    - Secondary Synchronization Pattern
- User Exploitation and Performance
- Deployment Status

# I/NAV Improvement - Content

- I/NAV improvement provides benefits along 3 axis
  - **Improved Time to First Fix** - fast retrieval of navigation data
    **Improved data demodulation robustness** – demodulate nav data also in challenging environment
  - **Time ambiguity resolution** – for users with coarse time information (+/- 3 sec) to access Galileo system time without need to demodulate it from navigation message
- Implementation solution selected
  1. **Reduced Clock and Ephemeris** (redCED)
  2. **Reed Solomon** (RS)
  3. **Secondary Synchronisation Pattern** (SSP)
- Careful consideration of users
  - Improvements transparent to legacy users
  - Participating (new) users will take benefit


Public SIS-ICD contains I/NAV impr. spec since 01/2021

# Reduced Clock and Ephemeris Data

Basic Idea: Reduce the number of information required to generate a position fix (at cost of accuracy)

## I/NAV Clock and Ephemeris Parameter

- are spread over 4 I/NAV words (I/NAV-1, -2, -3, -4)
- all 4 I/NAV words need to be received (with same IODnav) to establish a position fix

| Parameter | Definition | Bits | Scale factor | Unit |
|---|---|---|---|---|
| $M_0$ | Mean anomaly at reference time | 32* | $2^{-31}$ | semi-circle** |
| $\Delta n$ | Mean motion difference from computed value | 16* | $2^{-43}$ | semi-circle/s** |
| e | Eccentricity | 32 | $2^{-33}$ | dimensionless |
| $A^{1/2}$ | Square root of the semi-major axis | 32 | $2^{-19}$ | $m^{1/2}$ |
| $OMEGA_0$ | Longitude of ascending node of orbital plane at weekly epoch*** | 32* | $2^{-31}$ | semi-circle** |
| $i_0$ | Orbit inclination angle at reference time | 32* | $2^{-31}$ | semi-circle** |
| OMEGA | Argument of perigee | 32* | $2^{-31}$ | semi-circle** |
| OMEGADOT | Rate of change of right ascension | 24* | $2^{-43}$ | semi-circle/s** |
| IDOT | Rate of change of inclination angle | 14* | $2^{-43}$ | semi-circle/s** |
| $C_{uc}$ | Amplitude of the cosine harmonic correction term to the argument of latitude | 16* | $2^{-29}$ | rad |
| $C_{us}$ | Amplitude of the sine harmonic correction term to the argument of latitude | 16* | $2^{-29}$ | rad |
| $C_{rc}$ | Amplitude of the cosine harmonic correction term to the orbit radius | 16* | $2^{-5}$ | m |
| $C_{rs}$ | Amplitude of the sine harmonic correction term to the orbit radius | 16* | $2^{-5}$ | m |
| $C_{ic}$ | Amplitude of the cosine harmonic correction term to the angle of inclination | 16* | $2^{-29}$ | rad |
| $C_{is}$ | Amplitude of the sine harmonic correction term to the angle of inclination | 16* | $2^{-29}$ | rad |
| $t_{0e}$ | Ephemeris reference time | 14 | 60 | s |
| **Total ephemeris bits** | | **356** | | |

**Table 7-2: Ephemeris parameters**

| Parameter | Definition | Bits | Scale factor | Unit |
|---|---|---|---|---|
| $t_{0c}$ | Clock correction data reference Time of Week | 14 | 60 | s |
| $a_{f0}$ | SV clock bias correction coefficient | 31* | $2^{-34}$ | s |
| $a_{f1}$ | SV clock drift correction coefficient | 21* | $2^{-46}$ | s/s |
| $a_{f2}$ | SV clock drift rate correction coefficient | 6* | $2^{-59}$ | $s/s^2$ |
| **Clock Correction Parameters** | | **72** | | |

**Table 7-5: Clock correction parameters**

## Reduced Clock and Ephemeris Parameter

- Idea: reduce number of CED parameters and bit allocation to squeeze all information into a single I/NAV word (**122 bits**)
- redCED
  - are derived **on-board** from full CED
  - provide degraded accuracy compared to CED
- User exploitation:
  - First position fix with redCED

| Parameter | Number of bits | Scale factor | Reference value | Unit |
|---|---|---|---|---|
| $\Delta A_{red}$ | 5* | $2^8$ | 29600000 | meter |
| $e_{xred}$ | 13* | $2^{-22}$ | 0 | dimensionless |
| $e_{yred}$ | 13* | $2^{-22}$ | 0 | dimensionless |
| $\Delta i_{0red}$ | 17* | $2^{-22}$ | 56/180 | semi-circle** |
| $\Omega_{0red}$ | 23* | $2^{-22}$ | 0 | semi-circle** |
| $\lambda_{0red}$ | 23* | $2^{-22}$ | 0 | semi-circle** |
| $a_{f0red}$ | 22* | $2^{-26}$ | 0 | s |
| $a_{f1red}$ | 6* | $2^{-35}$ | 0 | s/s |
| **Total bits** | **122** | | | |

**428 bits** → **122 bits**

# Reed Solomon Coding of the Clock and Ephemeris Data

Basic Idea: Introduce additional redundancy in navigation message to correct for lost or corrupted data

Introduction of Reed-Solomon Clock and Ephemeris Data (RS CED) to the I/NAV message (E1-B)

- RS coding provides
  - Correction of residual errors **AND** recovery of erased information
- 4 different RS CED word are generated **on-board** (obtained from CED), per sub-frame 2 RS CED words are broadcast
- Any set of four different error free received (RS) CED words recovers the CED
  - Examples:

# Secondary Synchronization Pattern

Basic Idea: Introduce defined bit pattern in msg that can be detected by correlation (no need to demodulate message)

Introduction of Secondary Synchronization Pattern (SSP) into the I/NAV message (E1-B) supports reconstruction of the GST, without the need to demodulate the navigation message

| | SSP1 | SSP2 | SSP3 |
|---|---|---|---|
| Plain SSP configurations | 00000100 | 00101011 | 00101111 |

- SSP replaces spare bits on E1-B
- Required level of coarse synchronisation
- Ambiguous Time Of Week (TOW) information can be retrieved
  - SSP1 detected → TOW modulo 6s = 1s
  - SSP2 detected → TOW modulo 6s = 3s
  - SSP3 detected → TOW modulo 6s = 5s

Enables fast GST recovery (modulo 6 seconds) already at symbol level

**E1-B**

| Sync | Symbols for Word i (2/2) | Total |
|---|---|---|
| 10 | 240 | 250 |

| Even/Odd=1 | Type=0 | Data i (2/2) | EDBS | SAR | Spare | CRC i | SSP | Tail | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 16 | 40 | 22 | 2 | 24 | 8 | 6 | 120 |

# Outline

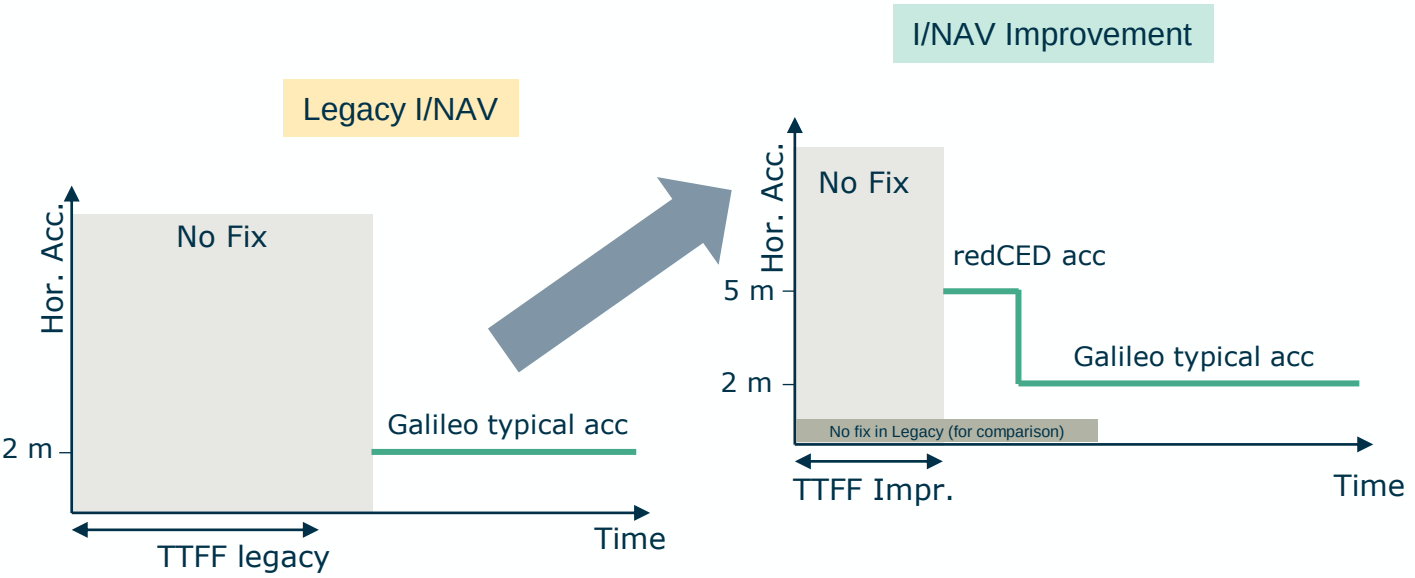
- I/NAV Improvement – User Benefits
- I/NAV Improvement – Technical Content
    - Reduced Clock and Ephemeris Data
    - Reed Solomon coded Clock and Ephemeris Data
    - Secondary Synchronization Pattern
- **User Exploitation and Performance**
- Deployment Status

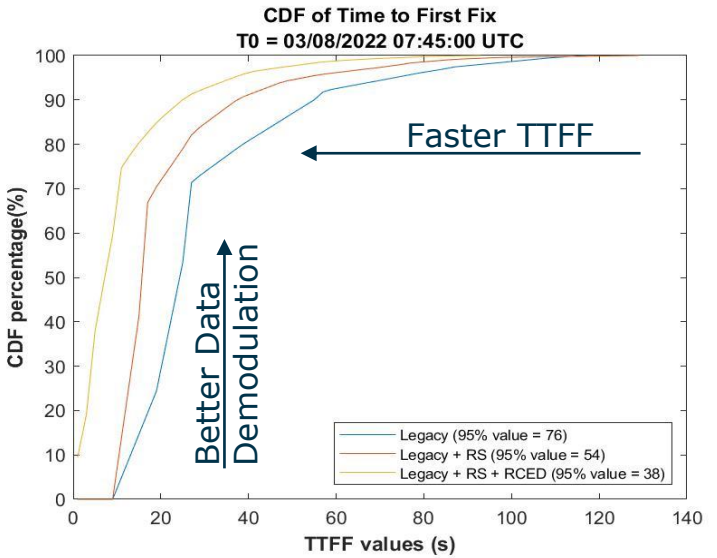
# RS-CED/redCED - User Exploitation and Performance (I)

- Faster Time to First Fix (TTFF)
- Better Data Demodulation Robustness

- Reduced Clock and Ephemeris (redCED)
- Reed Solomon Clock and Eph. Data (RS-CED)

- **Key** performance parameter from **user perspective is TTFF** (also as consequence of better data demodulation robustness)
- User performance improvement validated during I/NAV IOV in Urban Environment




**I/NAV Improvement provides 2-times faster First Fix with Galileo!**

# RS-CED/redCED - User Exploitation and Performance (II)

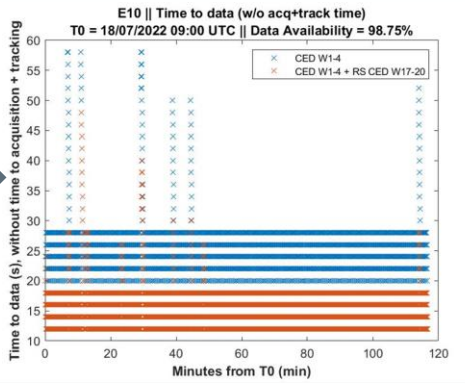
Reed Solomon Clock and Ephemeris Data (RS-CED) and redCED for improved Time to Data

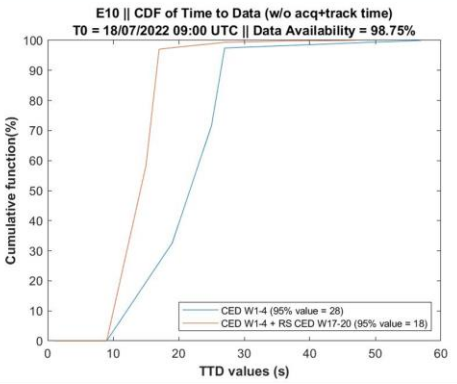
- Time to Data (TTD) – performance parameter on single link (different than Time to First Fix)
- Performance characterization in Open Sky Environment (makes it independent from local environment and deterministic)
- Time to Data for coarse accuracy (as per redCED performance characterization) and full accuracy:

| Parameter | Performance as measured (not a commitment) | Percentile |
|---|---|---|
| TTD [sec] for coarse accuracy with I/NAV improvement (redCED and RS-CED use) in Open Sky | 16* | 95% |
| TTD [sec] for full accuracy with I/NAV improvement (RS-CED use) in Open Sky | 22* | 95% |
| TTD [sec] for full accuracy w/o I/NAV improvement in Open Sky | 32* | 95% |

*: as per M. Paonni et al, Improving the Performance of Galileo E1-OS by Optimizing the I/NAV Navigation Message, ION 2019

## Validated in Orbit




- - - Dashed square area = typical Open Sky case

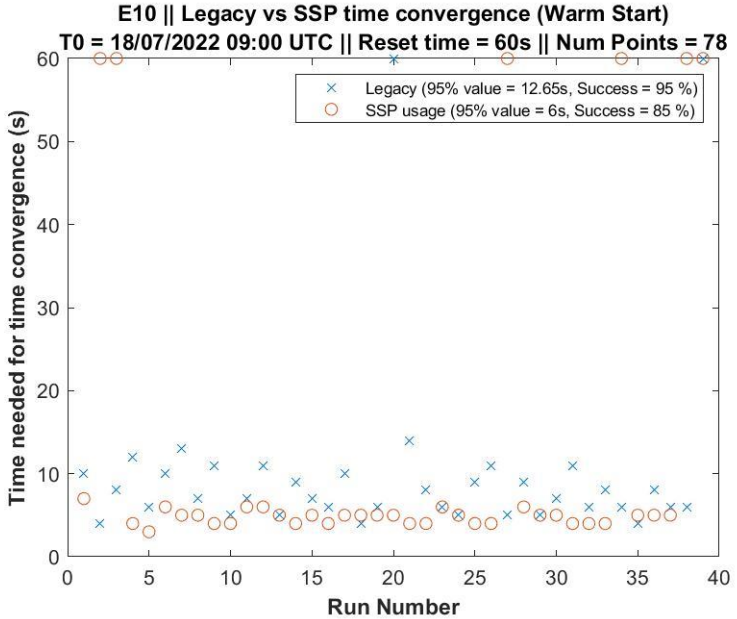
# SSP - User Exploitation and Performance (I)

- Time Ambiguity Resolution

- Secondary Synchronization Pattern (SSP)

| | SSP1 | SSP2 | SSP3 |
|---|---|---|---|
| Plain SSP configurations | 00000100 | 00101011 | 00101111 |

- **SSP** provide to users that already have coarse time information (+/- 1.5 sec) the means to resolve remaining time ambiguity and give access to the Galileo System Time. No need to demodulate time information from the navigation message.
- User performance improvement validated during I/NAV IOV in Urban Environment




Access to Galileo System Time is key for connected mass market users!

**I/NAV Improvement provides 2-times faster access to Galileo system time for users that have coarse time information in Urban Environment!**

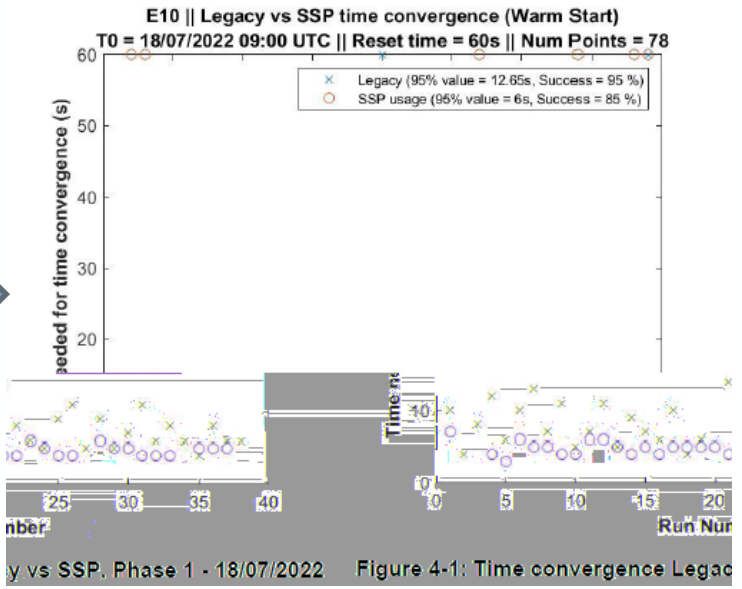
# SSP - User Exploitation and Performance (II)

## Secondary Synchronisation Pattern (SSP) for Time (GST) Dissemination

- Time to Time (TTT) – performance parameter on a single link for the provision of time (GST) information
  - Note: SSP provides time ambiguity resolution within interval of +/- 3 sec

**Validated in Orbit**

| Parameter | Performance as measured (not a commitment) | Percentile |
|---|---|---|
| TTT [sec] for time ambiguity (with SSP) in Open Sky | 6 | 95% |
| TTT [sec] for absolute time (with legacy I/NAV) in Open Sky | 13 | 95% |




y vs SSP. Phase 1 - 18/07/2022 Figure 4-1: Time convergence Legac

# Outline

- I/NAV Improvement – User Benefits
- I/NAV Improvement – Technical Content
    - Reduced Clock and Ephemeris Data
    - Reed Solomon coded Clock and Ephemeris Data
    - Secondary Synchronization Pattern
- User Exploitation and Performance
- **Deployment Status**

# I/NAV Improvement Deployment Status

I/NAV improvement is calculated on-board the satellite

- No change at Ground Mission Segment
- New software for signal generation unit available and under upload

Current Status

- 2 satellites (GSAT0223 and GSAT0224) already provide I/NAV improvement
- Remaining Galileo FOC satellites follow soon

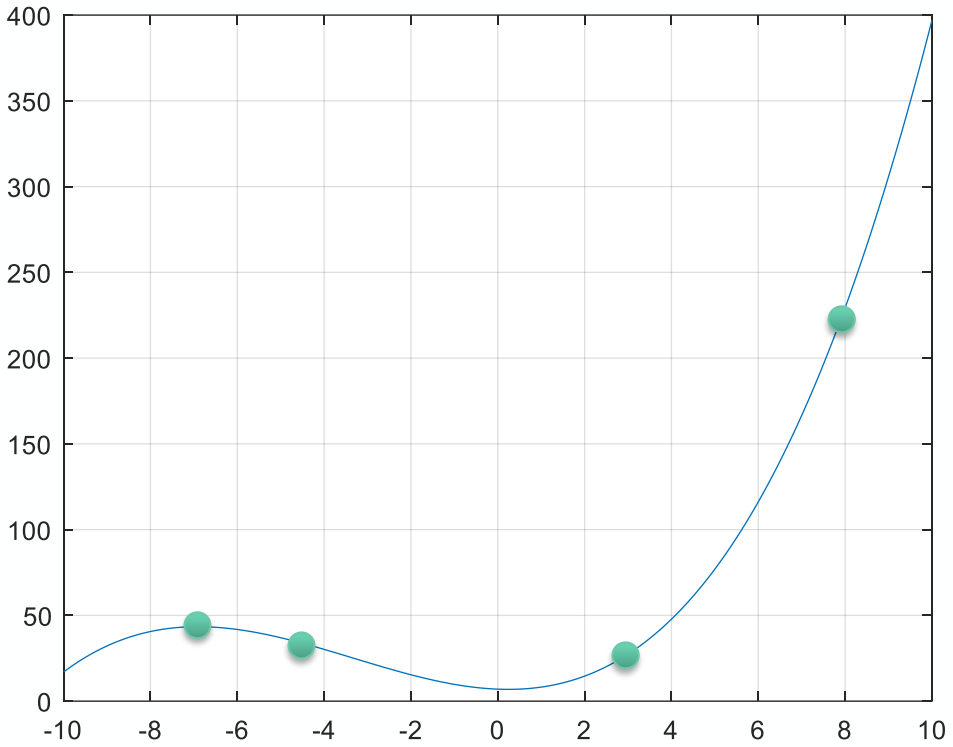
**I/NAV improvement is there – get ready to use it!**

# BACKUP MATERIAL

# Reed Solomon Coding of the Clock and Ephemeris Data

Basic Idea: Introduce additional redundancy in navigation message to correct for lost or corrupted data

Analogy for illustration

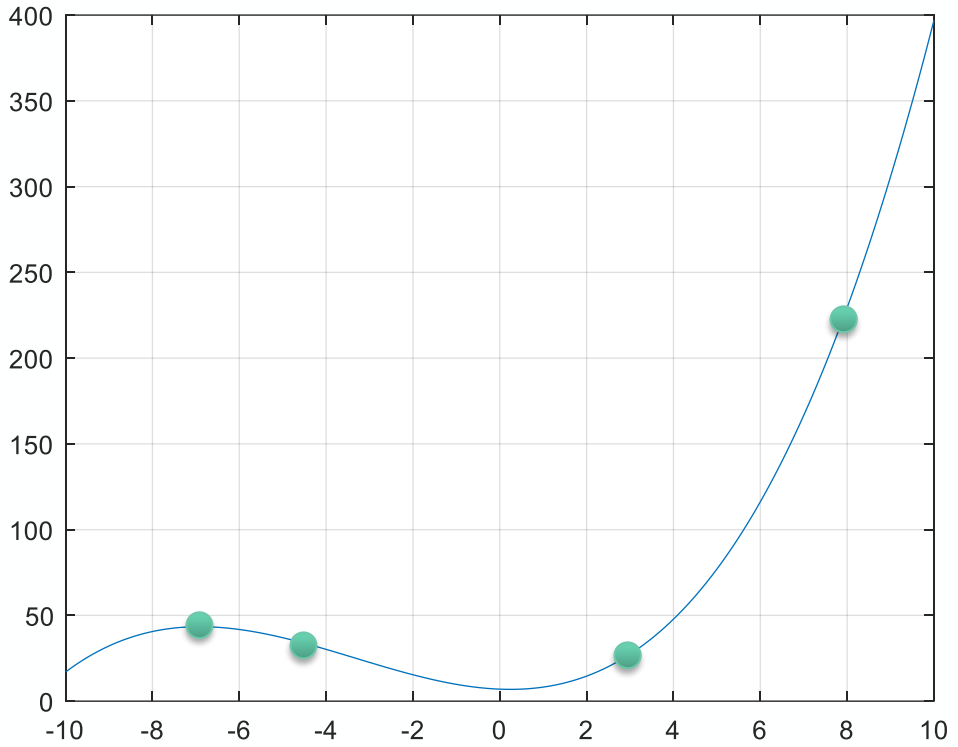



Polynomial of degree 3 $(y = ax^3 + bx^2 + cx + d)$

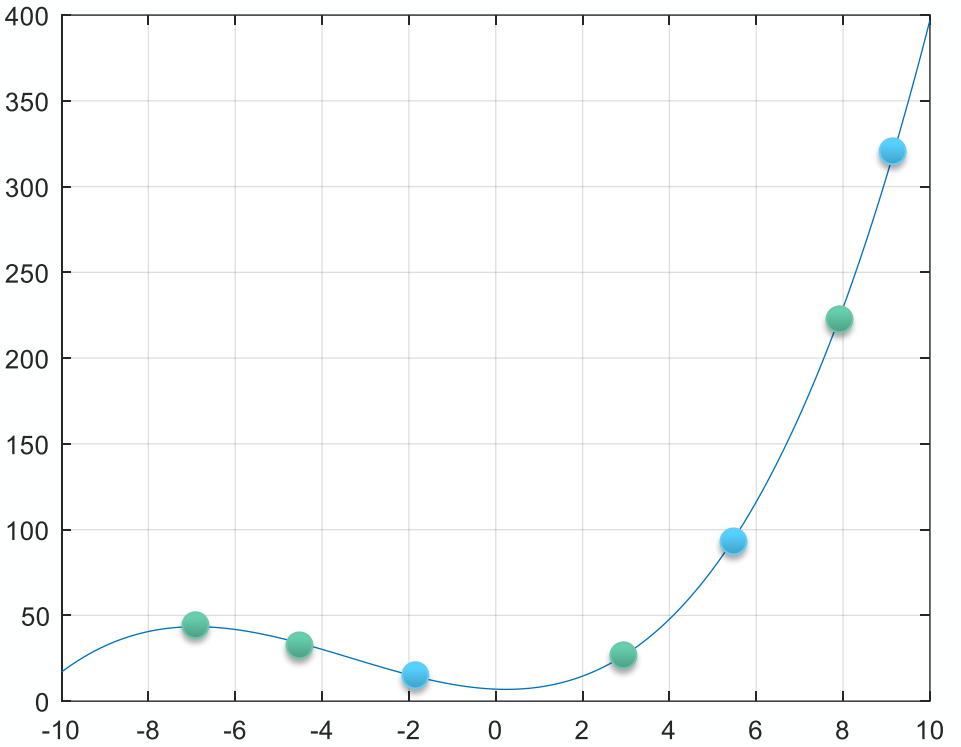
# Reed Solomon Coding of the Clock and Ephemeris Data

Basic Idea: Introduce additional redundancy in navigation message to correct for lost or corrupted data

Analogy for illustration




Polynomial of degree 3 $(y = ax^3 + bx^2 + cx + d)$

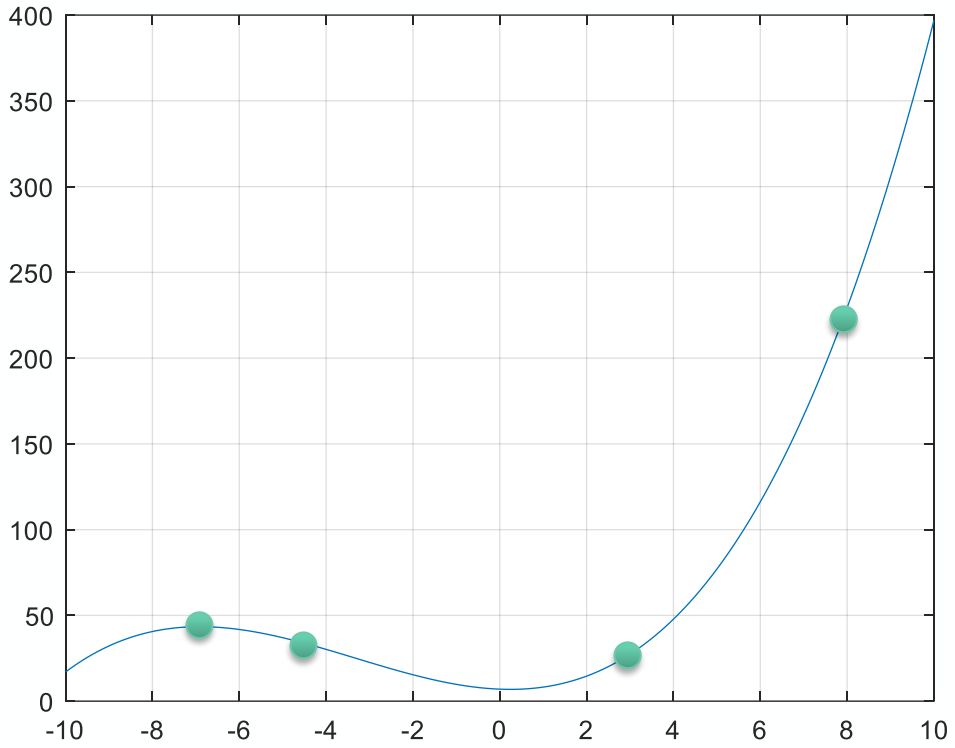



Introduce additional (redundant) grid points

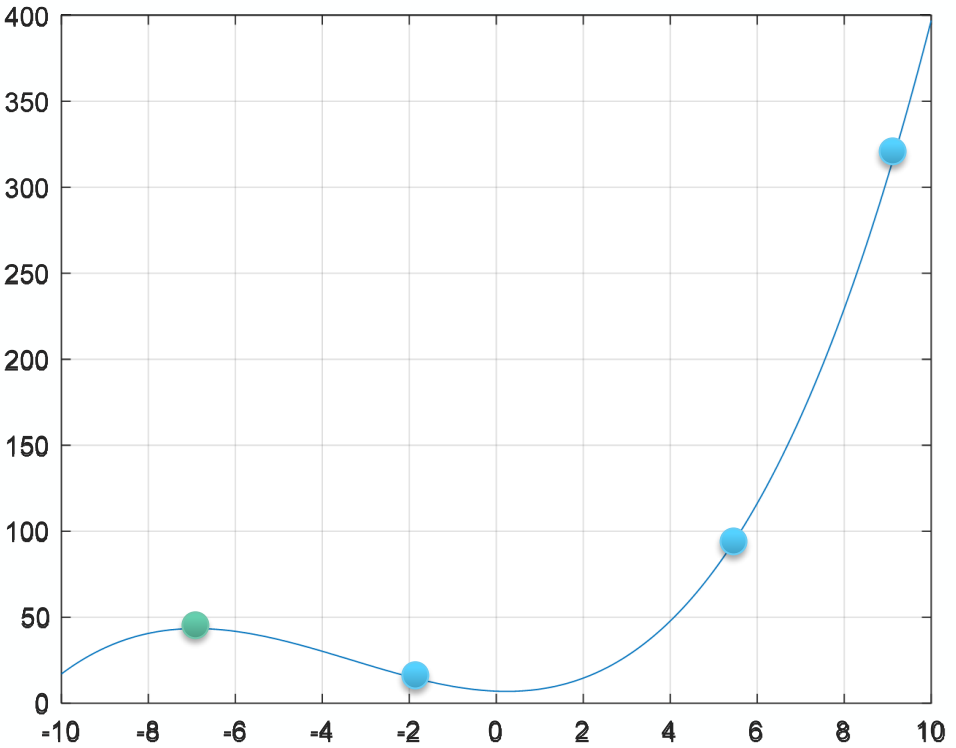
# Reed Solomon Coding of the Clock and Ephemeris Data

Basic Idea: Introduce additional redundancy in navigation message to correct for lost or corrupted data

Analogy for illustration




Polynomial of degree 3 ($y = ax^3 + bx^2 + cx + d$)

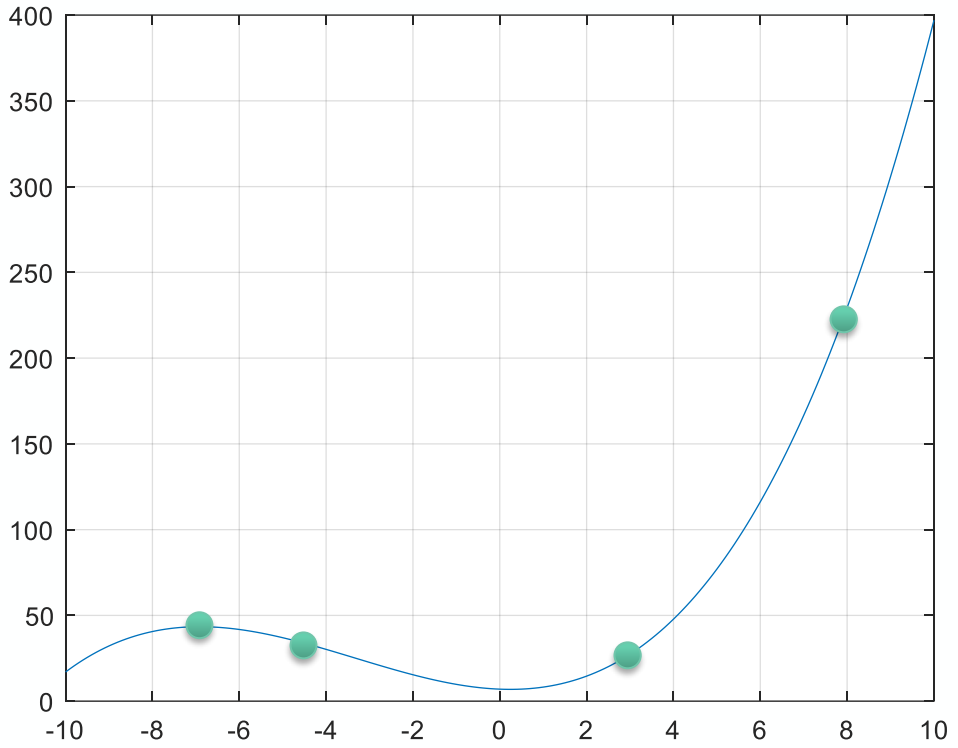



Loss of data (erasure correction)

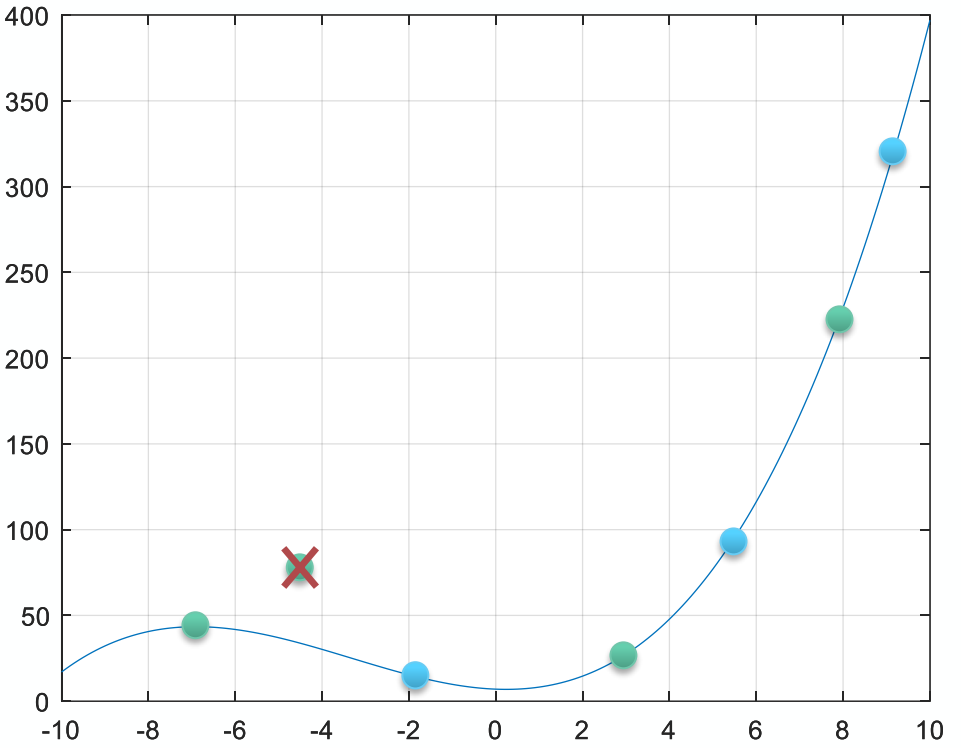
# Reed Solomon Coding of the Clock and Ephemeris Data

Basic Idea: Introduce additional redundancy in navigation message to correct for lost or corrupted data

Analogy for illustration




Polynomial of degree 3 $(y = ax^3 + bx^2 + cx + d)$




Error Correction