Galileo I/NAV Improvement

D/NAV

UNOOSA ICG Annual Meeting – October 2022

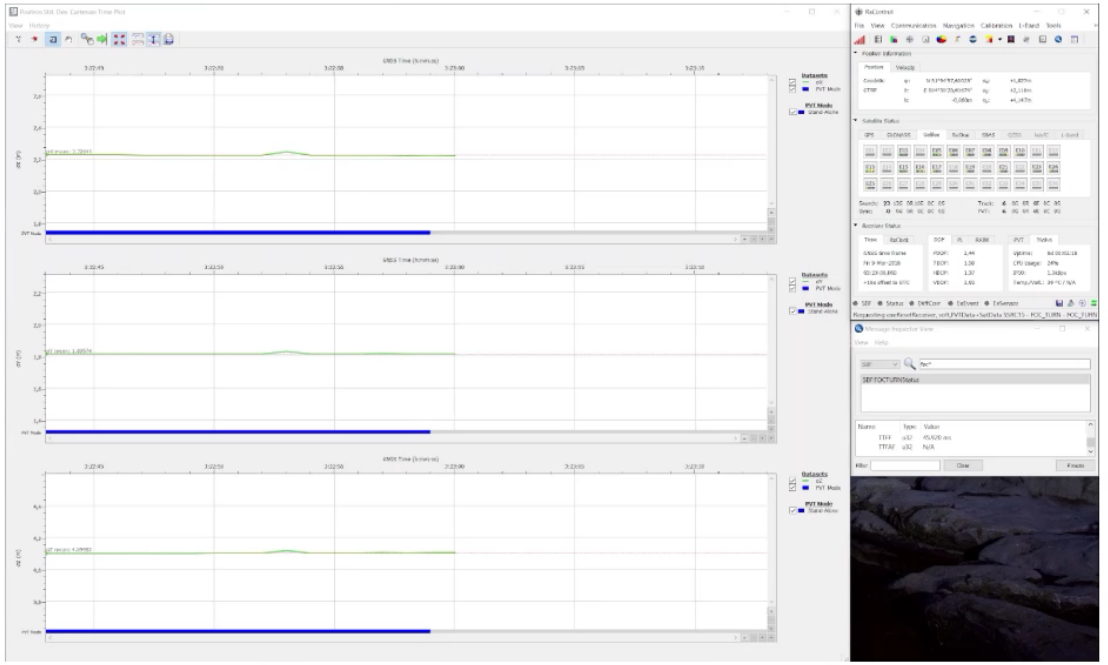
Outline

- **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

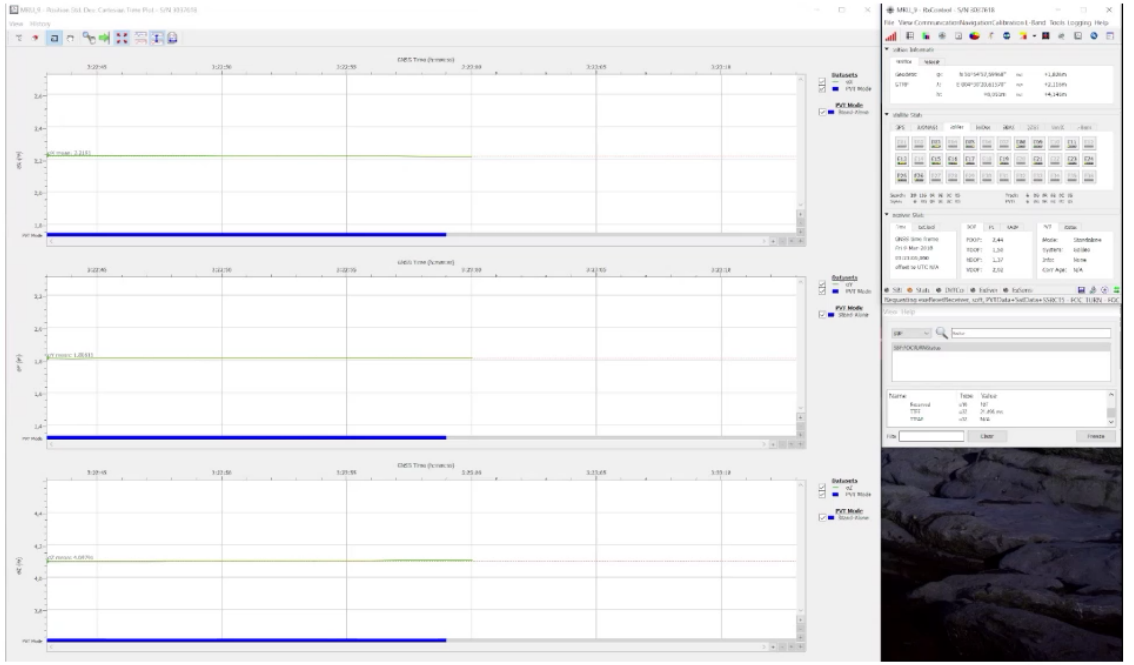
Position error (x,y,z) with **I/NAV Legacy**

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**
Δn	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
ΔA_{red}	5*	2^8	29600000	meter
e_{xred}	13*	2^{-22}	0	dimensionless
e_{yred}	13*	2^{-22}	0	dimensionless
Δi_{0red}	17*	2^{-22}	56/180	semi-circle**
Ω_{0red}	23*	2^{-22}	0	semi-circle**
λ_{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

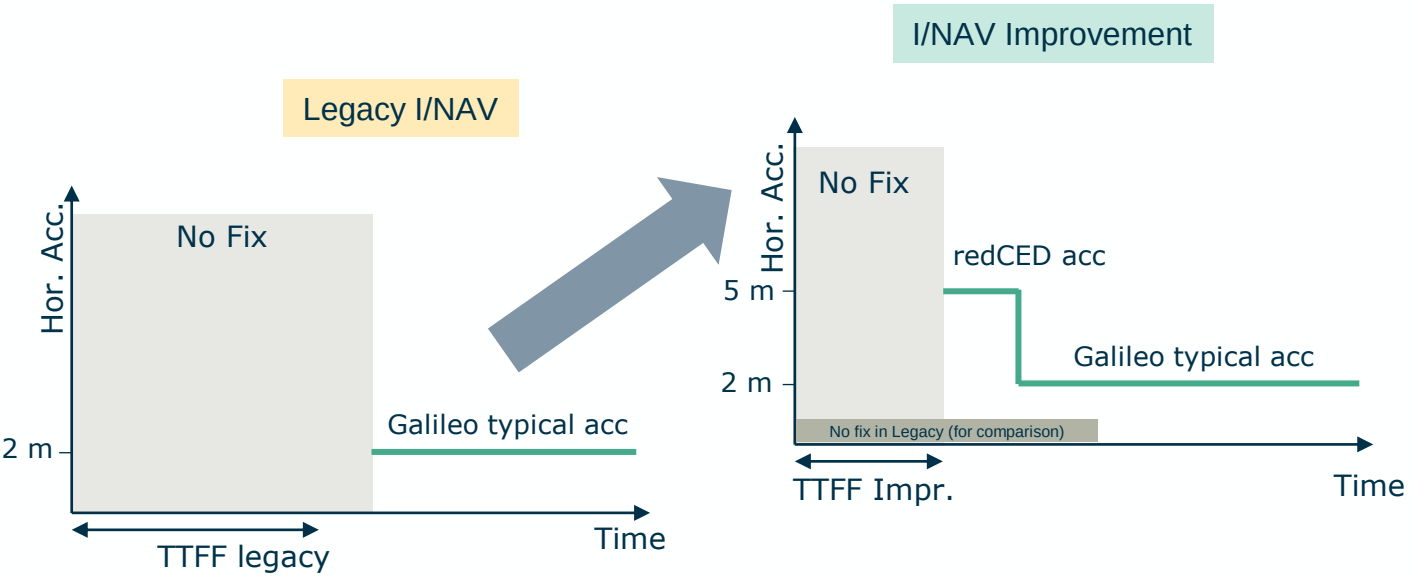
- I/NAV Improvement – User Benefits
- I/NAV Improvement – Technical Content
    - Reduced Clock and Ephemeris Data
    - Reed Solomon coded Clock and Ephemeris Data
    - Secondary Synchronization Pattern
- **User Exploitation and Performance**
- Deployment Status

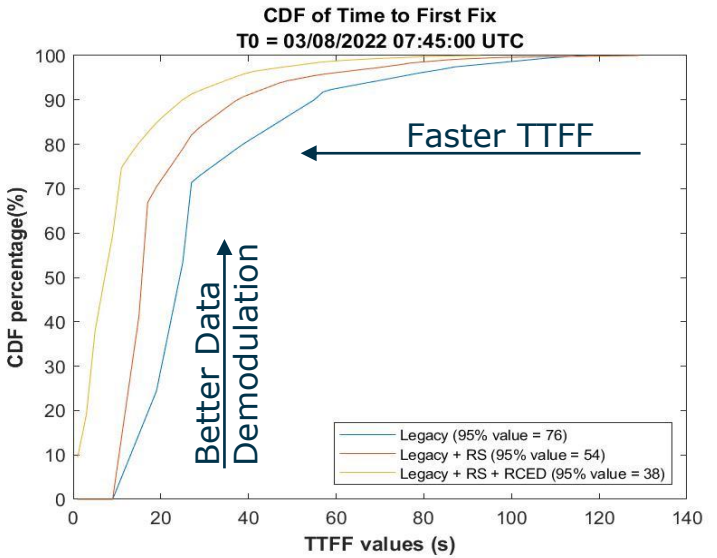
RS-CED/redCED - User Exploitation and Performance (I)

- 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)

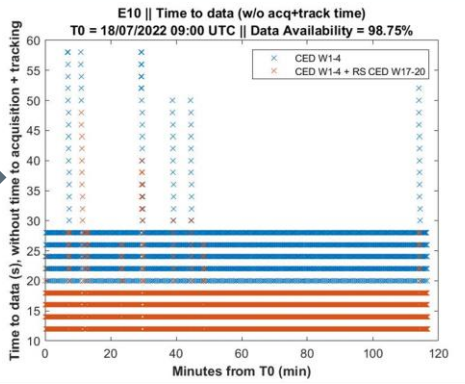
Reed Solomon Clock and Ephemeris Data (RS-CED) and redCED for improved Time to Data

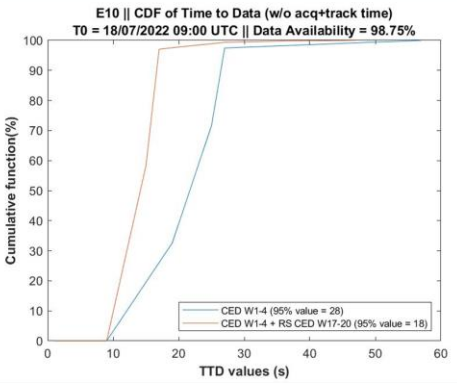
- Time to Data (TTD) – performance parameter on single link (different than Time to First Fix)
- Performance characterization in Open Sky Environment (makes it independent from local environment and deterministic)
- Time to Data for coarse accuracy (as per redCED performance characterization) and full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

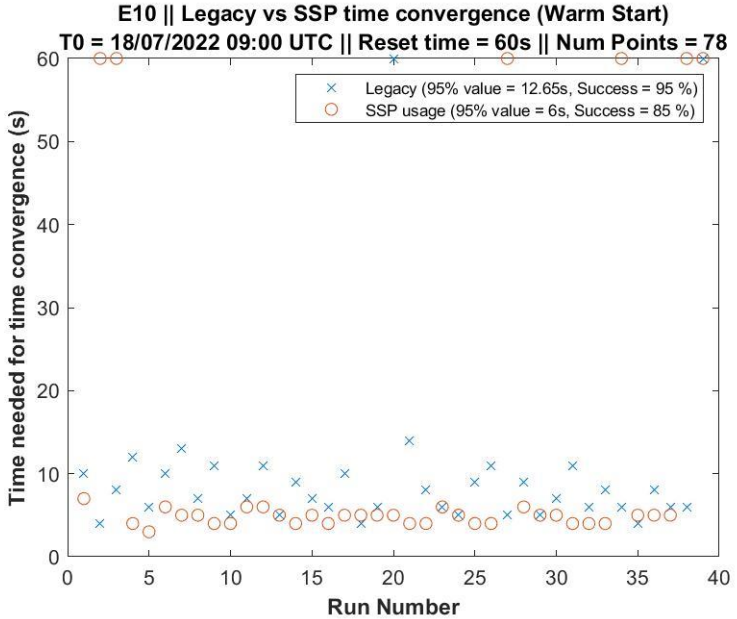
SSP - User Exploitation and Performance (I)

- 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%

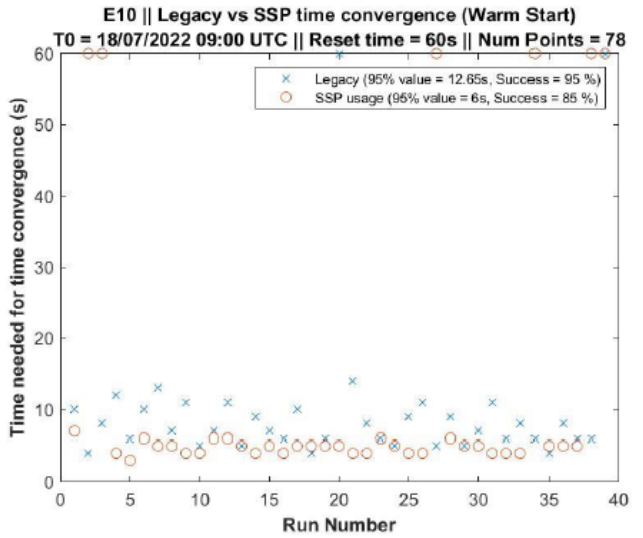


Figure 4-1: Time convergence Legacy vs SSP, Phase 1 - 18/07/2022

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 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

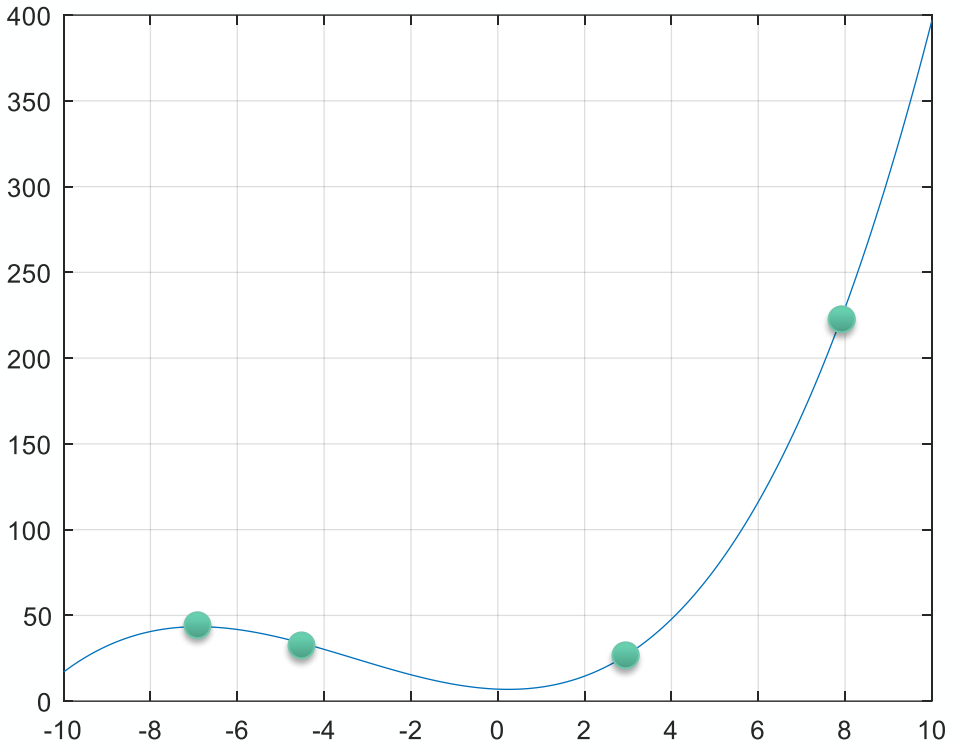
I/NAV improvement is there – get ready to use it!

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

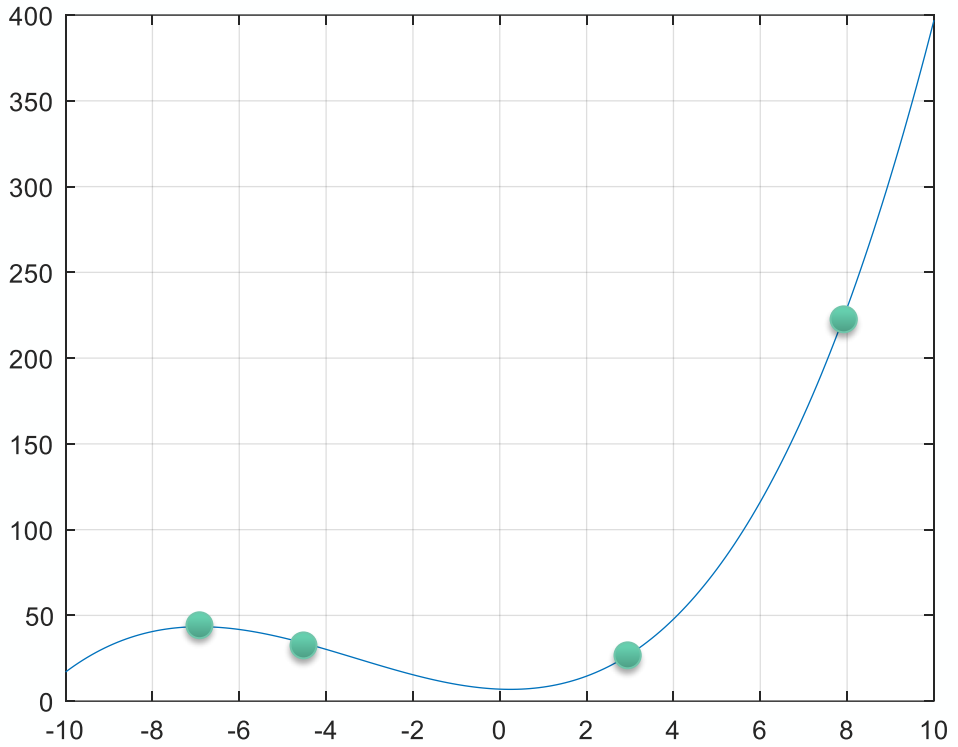


Polynomial of degree 3 $(y = ax^3 + bx^2 + cx + d)$

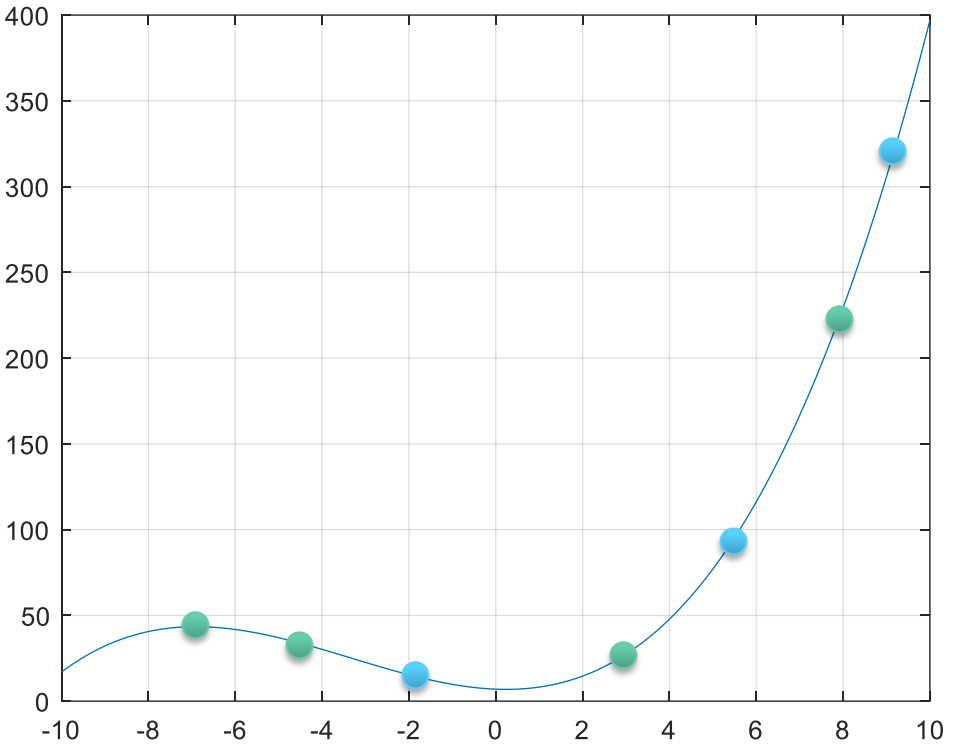
Reed Solomon Coding of the Clock and Ephemeris Data

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

Analogy for illustration



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

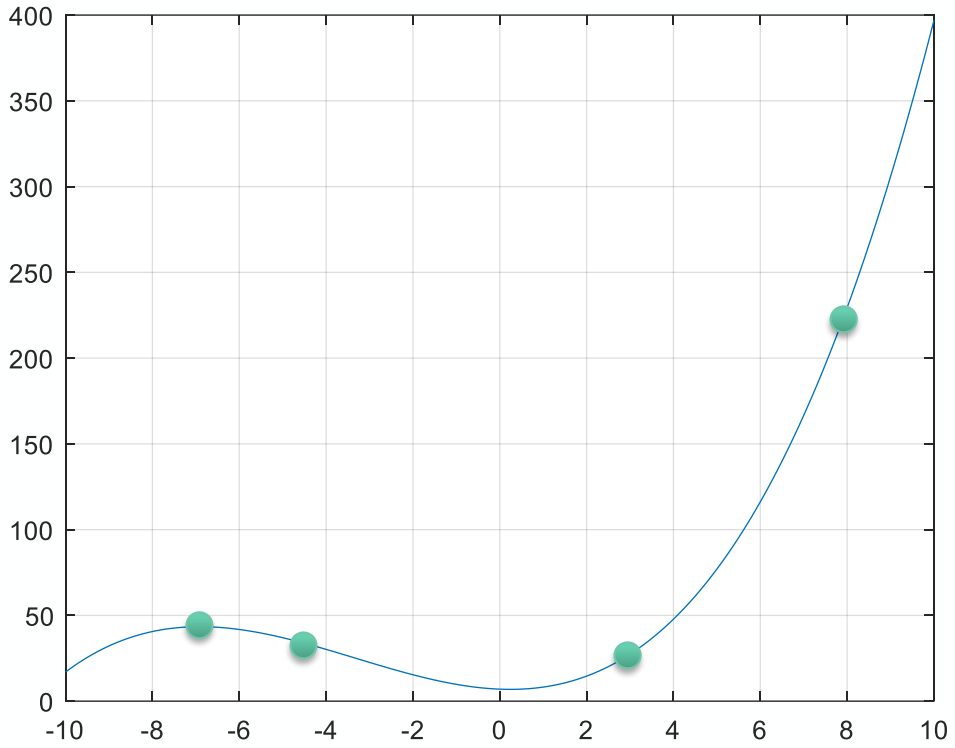


Introduce additional (redundant) grid points

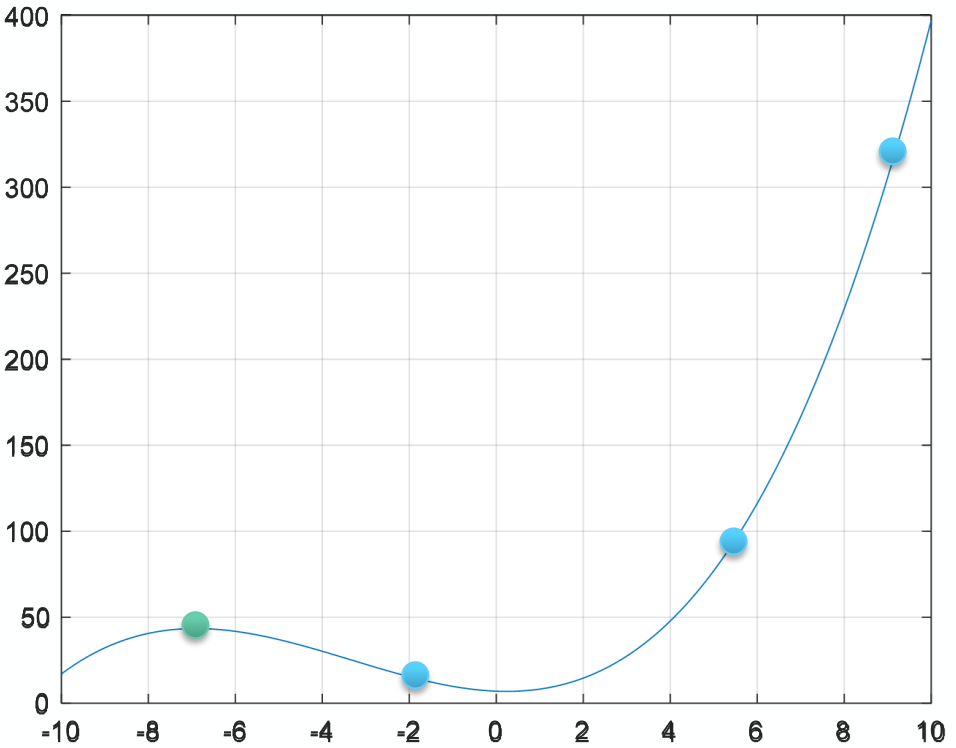
Reed Solomon Coding of the Clock and Ephemeris Data

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

Analogy for illustration



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

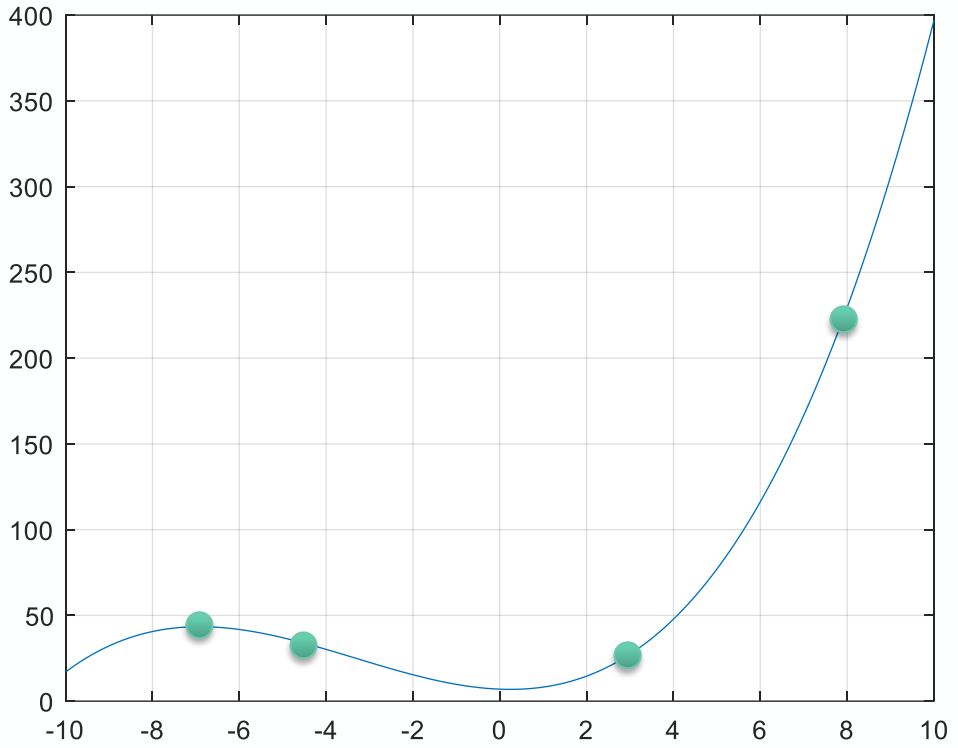


Loss of data (erasure correction)

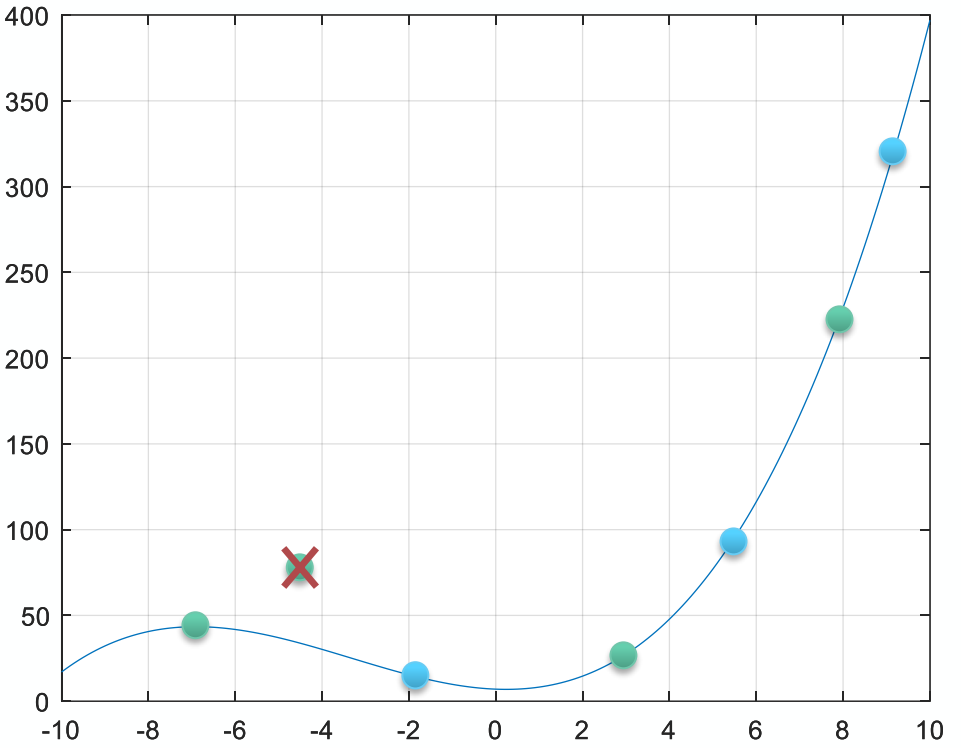
Reed Solomon Coding of the Clock and Ephemeris Data

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