Passive reception of Two-Way Satellite Time and Frequency Transfer (TWSTFT) signals from a geostationary satellite, or GPS upside down

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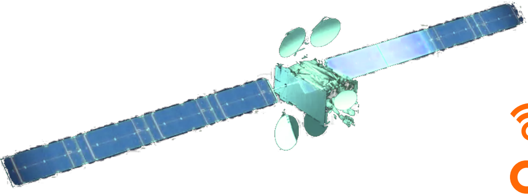
slides at `http://jmfriedt.free.fr/grcon2022.pdf`

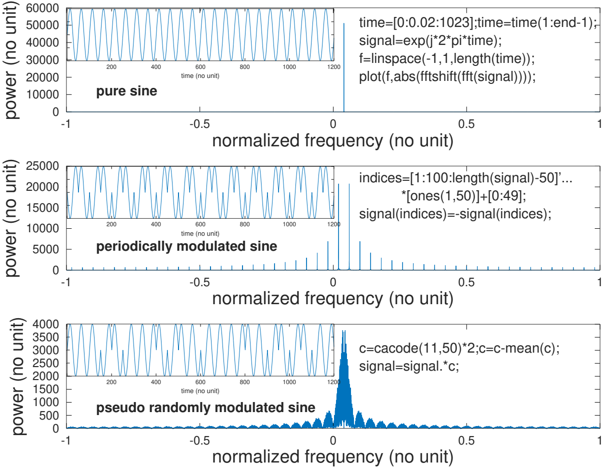


26-30 September 2022

Time v.s. frequency

- clock on both ends are not running at the same rate
- clock on both ends are not phase synchronized (time delay)
- the only known timestamp is when sampling the incoming signal by the ADC ⇒ the ADC clock **must be referenced** to the disciplined/reference oscillator
- Timetech's **SATRE** (Satellite Time- and Ranging Equipment [a]) uses communication layers (OSI layer >0) for sharing timestamps

[a] `https://www.ion.org/ptti/upload/files/1039_10139_Datasheet.pdf`



Frequency offset correction needed for correlation: postprocessing in SDR approach

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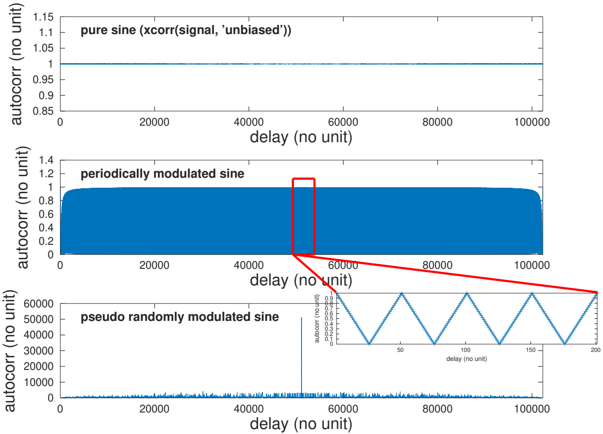
$$FT(xcorr(x,y)(\tau)) = FT(x)\cdot FT^*(y)$$

$$\Rightarrow FT(xcorr(x,x)) = |FT(x)|^2$$



Frequency offset correction needed for correlation: postprocessing in SDR approach

[a] https://www.ion.org/ptti/upload/files/1039_10139_Datasheet.pdf

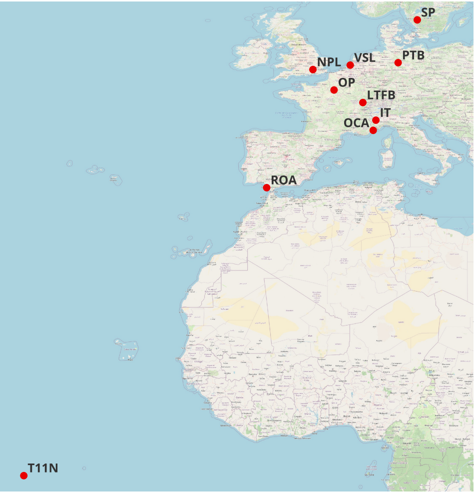
Two-way time transfer

Temps Atomique International[1] results from averaging multiple (500 in 2016) atomic clocks (primary references[2]) over the world (>70 laboratories)

- Speed of light: 300 m/μs
- MIFID II/high frequency trading[3]: financial transactions must be timestamped to better than 100 μs accuracy, 1 μs resolution
- 5G: $\leq$ 260 ns
- smart grid: $\leq$ 100 ns (<10 m fault detection) [4]

Need for time of flight compensation $\Rightarrow$ TWSTFT

Question: are these signals usable for one-way T&F dissemination?



[1] `https://www.bipm.org/en/time-metrology`

[2] `https://www.lne.fr/en/learn-more/international-system-units/second`: the definition of the second is the duration of 9,192,631,770 transitions between two hyperfine levels of the ground state of the cesium-133 atom

[4] European Global Navigation Satellite System Agency, *Report on Time & Synchronization User Needs and Requirements GSA-MKD-TS-UREQ-250285* (2018)

[4] `https://wsts.atis.org/wp-content/uploads/sites/9/2018/12/P-07_Nguyen_NIST_Timing-Challenges-in-Smart-Grid.pdf`

Receiving TWSTFT with a consumer television satellite parabolic antenna

Reception conditions available from public information:

- European downlink frequency from Telstar11N[a] [b] [c] : 10.96015 GHz
- Communication every even UTC hour [d]
- Each communicating station is frequency offset[e]

[a] C. Rieck, P. Jarlemark & K. Jaldehag, *Utilizing TWSTFT in a Passive Configuration*, Proc. 48th Annual Precise Time and Time Interval Systems and Applications Meeting (2017)

[b] C. Rieck, P. Jarlemark & K. Jaldehag, *Passive Utilization of the TWSTFT Technique*, Proc EFTF (2018)

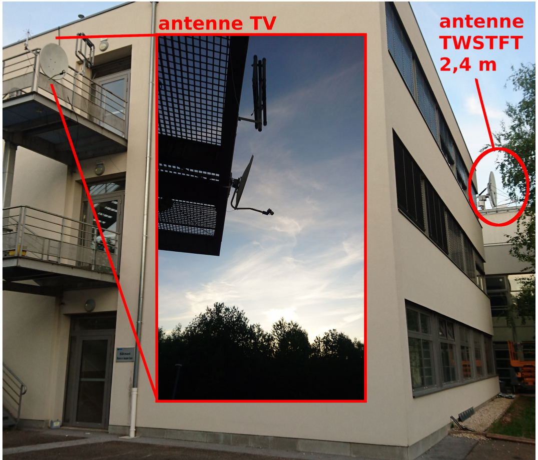
[c] CCTF/17-20, *RISE Research Institutes of Sweden, Report on Activities to the 21th meeting of the Consultative Committee for Time and Frequency, June 2017* section 7.2. Passive Utilization of TWSTFT

[d] V. Zhang & al., *A Study on Using SDR Receivers for the Europe-Europe and Transatlantic TWSTFT Links*, Proc. 2017 Precise Time and Time Interval Meeting (2017)

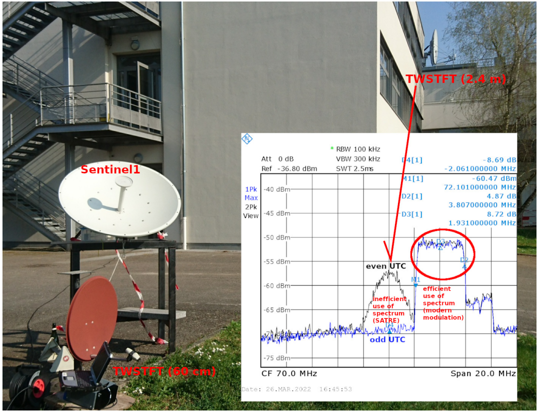
[e] A. Kanj, *Étude et développement de la méthode TWSTFT phase pour des comparaisons hautes performances d'étalons primaires de fréquence*, thèse Univ. Pierre & Marie Curie (2012), p.53

Objectives: receiving TWSTFT signals @ 11 GHz from Telstar11N (37.5° W geostationnary) downlink

- Time & frequency synchronization signals broadcast every even UTC hour from metrology laboratories
- BPSK signal received allowing for frequency correction ...
- ... and SATRE modem codes correlated with consistent frequency offset



Receiving TWSTFT with a consumer television satellite parabolic antenna



Experimental setup: completement 2.4 m parabola with COTS TV receiving equipment and B210 SDR receiver

- TV-satellite reception LNB oscillator at 9.75 GHz ...
- ... brings TWSTFT signal at 1.21 GHz within SDR receiver range, recorded at 10 MS/s (complex IQ)

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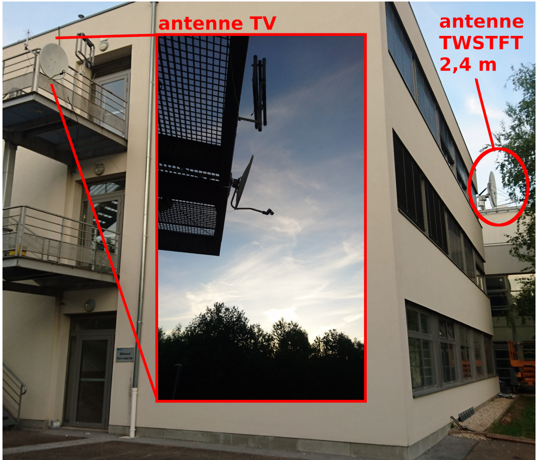

Time and frequency transfer

Telstar11N located 37.5°W views both North-America and Western Europe (at grazing angle!)

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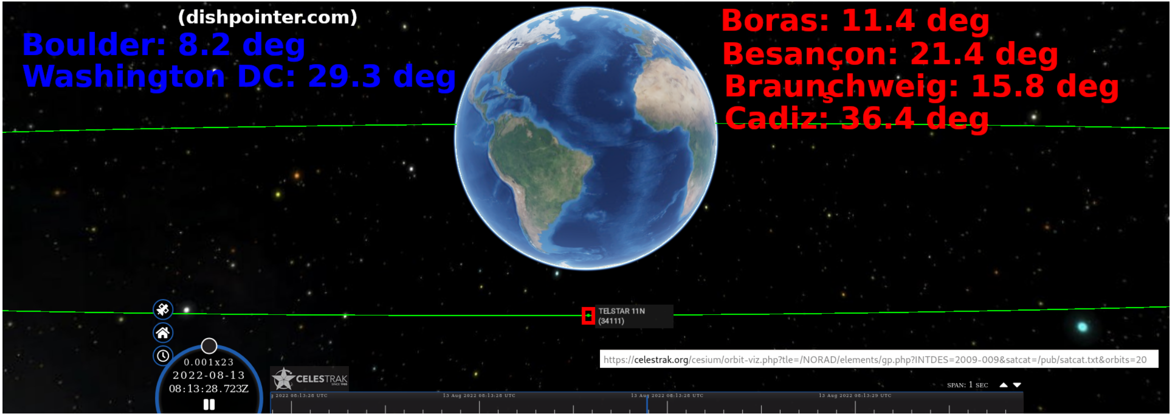
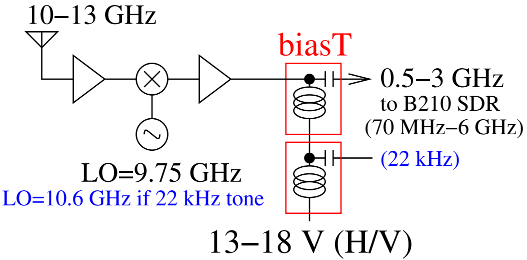
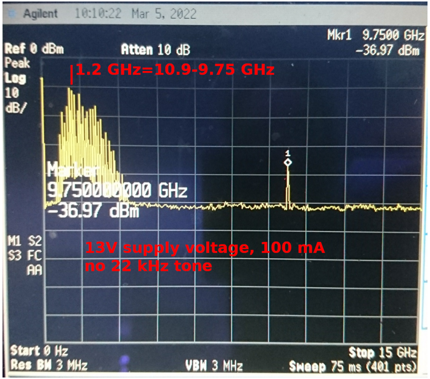


3D view courtesy of `celestrak.org`: despite 36000 km altitude, a geostationary satellite can hardly view above 75° (communication) or 60° (weather imaging)

Low Noise Block (LNB)

- amplification + frequency transposition to intermediate frequency
- supply voltage through a bias-T: 13 or 18 V selects polarization (H vs V)
- frequency transposition: local oscillator is 9.75 GHz (can jump to 10.60 GHz when injecting a 22 kHz tone through the bias-T)
- feed **Ettus Research B210** receiver with IF (1.204 GHz) signal
- RTL-SDR lacks bandwidth (5 MHz needed) but also demonstated with **RSP1** SDRPlay clone
- datastream: 5 MS/s×2 bytes/sample×2 samples/complex= 20 MB/s=1.2 GB/min





Receiving TWSTFT signals in the USA

```
* twop59.584
* FORMAT    01
* LAB       OP
* REV DATE  2021-08-24
* ES    OP01 LA: N  48 50 09.236      LO: E  02 20 05.873    HT:     78.00 m
* REF-FRAME ITRF88
* LINK   23 SAT: TELSTAR 11N          NLO: E 322 27 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 10953.9500 MHz   SAT-NRX: 14253.9500 MHz   BW:    4.1 MHz
* LINK   21 SAT: TELSTAR 11N          NLO: E 322 27 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 11497.0600 MHz   SAT-NRX: 14047.7400 MHz   BW:    3.9 MHz
* CAL   095 TYPE: PORT ES REL         MJD: 53684   EST. UNCERT.:     1.100 ns
```

https://webtai.bipm.org/ftp/pub/tai/data/2022/time_transfer/twstft//op/

```
* TWNIST59.584
* FORMAT    01
* LAB       NIST
* REV DATE  2021-07-07
* ES NIST01 LA: N  39 59 45.000      LO: W 105 15 46.000    HT: +1640.00 m
* REF-FRAME WGS84
* LINK   13 SAT: TELSTAR 11N          NLO: E 322 30 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 11726.5500 MHz   SAT-NRX: 14285.550 MHz   BW: 2.5MHz
* LINK   15 SAT: TELSTAR 11N          NLO: E 322 30 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 11746.5900 MHz   SAT-NRX: 14298.430 MHz   BW: 1.6MHz
* LINK   16 SAT: TELSTAR 11N          NLO: E 322 30 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 11746.5900 MHz   SAT-NRX: 14289.060 MHz   BW: 1.6MHz
* LINK   20 SAT: TELSTAR 11N          NLO: E 322 27 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 11747.7400 MHz   SAT-NRX: 14297.060 MHz   BW: 3.9 MHz
* CAL   071 TYPE: Cir.T(NPL1)         MJD: 53152   EST. UNCERT.:     5.000 ns
```

https://webtai.bipm.org/ftp/pub/tai/data/2022/time_transfer/twstft//nist/

```
* twusno59.583
* FORMAT    01
* LAB       USNO
* REV DATE  2021-05-27
* ES USNO01 LA: N  38 55 14.000      LO: W  77 04 00.100    HT:     46.90 m
* REF-FRAME WGS84
* LINK   20 SAT: TELSTAR 11N          NLO: E 322 30 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 11747.7400 MHz   SAT-NRX: 14297.0600 MHz   BW: 3.9 MHz
* CAL   458 TYPE: TRIANGLE CLOSURE    MJD: 59032   EST. UNCERT.:     3.000 ns
```

https://webtai.bipm.org/ftp/pub/tai/data/2022/time_transfer/twstft//usno/

Invaluable resource: BIPM ftp server where data shared between observatories are stored: `https://webtai.bipm.org/ftp/pub/tai/data/2022/time_transfer/twstft/`

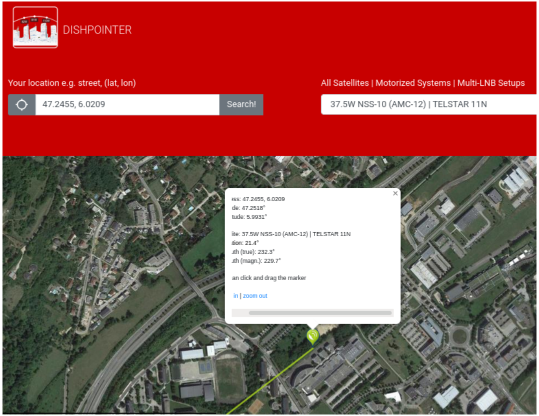
- Europe: 10.95395 GHz
- NIST (Boulder, Colorado)
- USNO (Washington DC)

Dowlink frequency: 11.49706 & 11.74774 GHz $\Rightarrow\simeq$ 1.7-2 GHz after transposition **or** inject a 22 kHz signal through the LNB bias T to switch LO to 10.6 GHz $\Rightarrow\simeq$1 GHz

Antenna geometry

If a television reception antenna is enough to receive the signal, why a 2.4 m parabolic reflector?

- ~~Antenna gain~~ (2.4 → 0.6 m parabola: 49 to 37 dB gain)
- Antenna directivity [a]



https://www.n2yo.com/satellites/?c=10&srt=11&dir=1

dishpointer.com

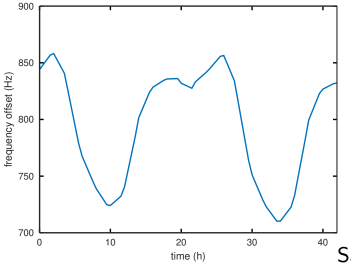
INTELSAT 14	36097	2009-064A	November 23, 2009	1436.1	45° W
USA 7	15453	1984-129A	December 22, 1984	1456.6	44.4° W
INTELSAT 32E (SKY BRASIL 1)	41945	2017-007B	February 14, 2017	1436.1	43.2° W
INTELSAT 11 (PAS 11)	32253	2007-044B	October 5, 2007	1436.1	42.9° W
SESAT 2 (EXPRESS AM-22)	28134	2003-060A	December 28, 2003	1449.3	42.9° W
USA 170	27875	2003-040A	August 29, 2003	1436.1	42.3° W
EUTELSAT 2-F2	21056	1991-003B	January 15, 1991	1455.4	42.2° W
KALPANA 1 (METSAT 1)	27525	2002-043A	September 12, 2002	1464.3	42.1° W
EXPRESS AM-11	28234	2004-015A	April 26, 2004	1451.1	41.5° W
TDRS-12	39504	2014-004A	January 23, 2014	1436	40.9° W
SES-6	39172	2013-026A	June 3, 2013	1436.1	40.5° W
ARABSAT 1D (ANIK D2)	15383	1984-113B	November 8, 1984	1455.9	39.3° W
USA 252	39751	2014-027A	May 22, 2014	1436.1	38° W
TELSTAR 11N	34111	2009-009A	February 26, 2009	1436.1	37.6° W
NSS 10 (AMC-12)	28526	2005-003A	February 3, 2005	1436.1	37.5° W
EUTE 36A (EUTE W4)	26369	2000-028A	May 24, 2000	1462.4	36.7° W
GARUDA 1	26089	2000-011A	February 12, 2000	1441.2	36.7° W
ITALSAT 2	24208	1996-044A	August 8, 1996	1428.9	36.6° W
HISPASAT 36W-1	41942	2017-006A	January 28, 2017	1436.1	36° W
MARECS B2	15386	1984-114B	November 10, 1984	1501.1	35.6° W
THAICOM 1	22931	1993-078B	December 18, 1993	1451.8	35.2° W
INTELSAT 605	21653	1991-055A	August 14, 1991	1449.7	34.5° W
INTELSAT 35E	42818	2017-041A	July 5, 2017	1436.1	34.5° W
AURORA 2	21392	1991-037A	May 29, 1991	1454.3	34.4° W
OPS 6391 (FLTSATCOM 1)	10669	1978-016A	February 9, 1978	1454.5	34.2° W
SPACENET 3R	18951	1988-018A	March 11, 1988	1444.8	34.1° W

[a] Eutelsat, *Antenna and VSAT Type Approval/Characterization*, ESOG 120 – Issue 8 - Rev. 1 (May 2021)

Carrier frequency offset[5]

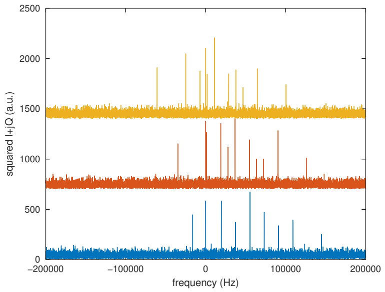
Europe	TX Offset (kHz)		TX Offset (kHz)
OP01	-8.944	OCA01	26.833
NPL01	0.000	IT02	-26.833
VSL01	8.944	**ROA01**	**-44.721**
SP01	-17.889	CH01	4.472
PTB01	17.889	TIM01	-13.416

- Frequency fluctuation of 2-day measurements (satellite transponder, **LNB** & SDR receiver)

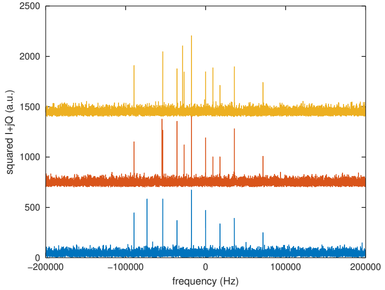


Satellite frequency shift/24h

- Identify carrier by squaring BPSK modulation & attribute lowest frequency offset to the known observatory



Before↑ After↓



[5] A. Kanj, *Étude et développement de la méthode TWSTFT phase pour des comparaisons hautes performances d'étalons*, PhD SYRTE/UPMC (2012)

Time and frequency transfer over geostationnary satellite links

SATRE modem, sequel to MITREX modem (1980s) developed in Stuttgart, proprietary hardware manufactured and sold by Timetech (Germany)

No (publicly) available documentation on the link characteristics [6] but

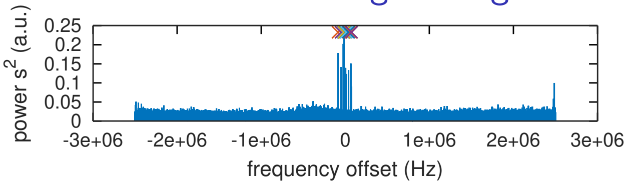
> These constraints have been met by the MITREX MODEM. It is an interface between the 70-MHz IF of a standard earth station, a Time Interval Counter TIC and the time keeping hardware, i.e. the atomic clock. The hardware is housed in a 19-inch drawer and operates as a pseudorandom noise sequence (PN) encoder/decoder of the time signal. The PN-code is a truncated maximum length sequence of period 10.000, instead of the 16.383 chips. This period of 10.000 eases the overall system design, as it allows the use of even and decimal dividers for signal processing. The correlation features of the maximum length sequence are almost retained.
>
> 2.2 PN-Encoding/Decoding

- $16383 = 2^{14} - 1$ and there are "only" [a] 756 possible maximum length sequence generators
- truncation to 10000-long, but we do not know what is the starting point
- Bit rate of 2.5 Mb/s: code repeats every 4 ms (10 ms @ 1 Mb/s)
- All 0s is a forbidden state (XOR(0,0)=0) so we might start with all 1s
- Calculate all possible codes, interpolate to match sampling rate, store their Fourier transform ...
- ... and for all possible frequency offset identified by squaring the signal (cancelling BPSK modulation), matrix product of FFT(signal) with stored FFT of codes
- iFFT will display correlation peaks if patterns match.

[a] `https://users.ece.cmu.edu/~koopman/lfsr/`

[6] P. Hartl, *Present state of long distance time transfer via satellites with application of the Mitrex modem* (1986)

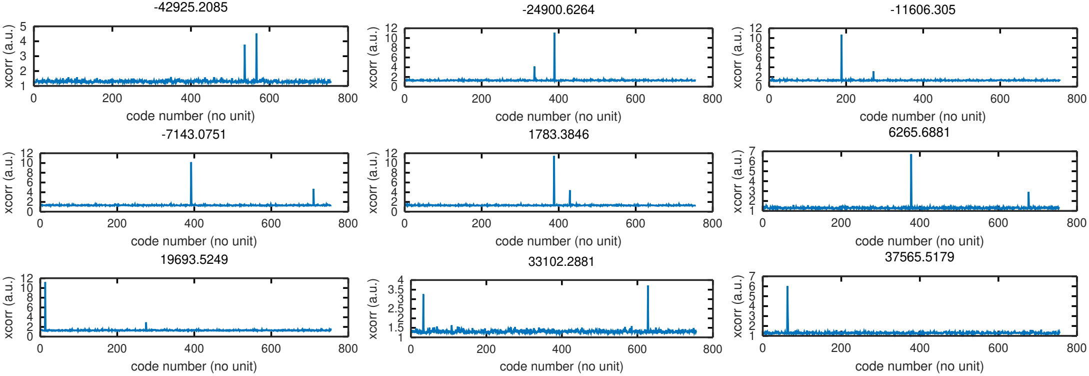
SATRE code reverse engineering



$$s(t) = \exp(j\delta\omega t + j\underbrace{\varphi}_{\{0;\pi\}})\text{ for BPSK modulation}$$

$$\Rightarrow s^2(t) = \exp(j2\delta\omega t)\text{ since }2\times\{0;\pi\} = 0[2\pi]$$

For all possible frequenycy offsets, run all possible LFSR codes (indexed on the abscissa)



SATRE code reverse engineering

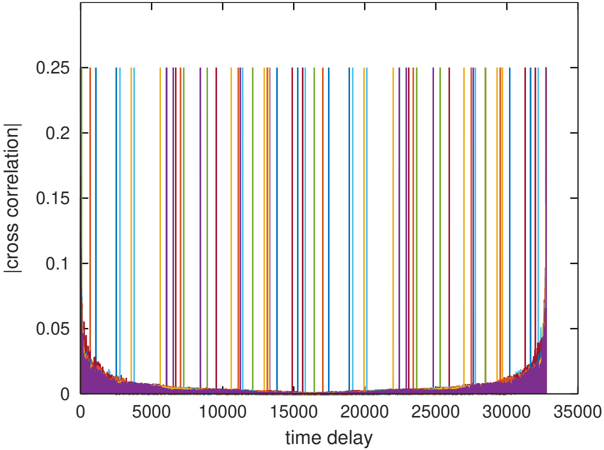
All 0s is forbidden state ⇒ start with all 1s

C (Galois LFSR)

```
#define L 16383 // 10000
for (i=0; i<14;i++) reg[i]=1; // 0x3FFF
for (i=0; i<L; i++)
  {code[i]=reg[0];
   shift_back=reg[0];
   for (j=1; j<14; j++)
      if (tap[prnno][j]==1)
        shift_back^=reg[j];
   for (j=1; j<14; j++)
      reg[j-1]=reg[j];
   reg[13]=shift_back;
  }
```

Octave/Matlab (Fibonacci LFSR)

```
start=0x3fff;
lfsr=uint16(start);  % starting value.
i=1;
do
    y(i)=bitand(lfsr, uint16(1));%save lsb
    if bitand(lfsr, uint16(1))
       lfsr=bitxor(bitshift(lfsr,-1),uint16(feedback));
    else
       lfsr=bitshift(lfsr,-1);
    end
    i=i+1;
until (lfsr==start); % max length LFSR must be 16383
```

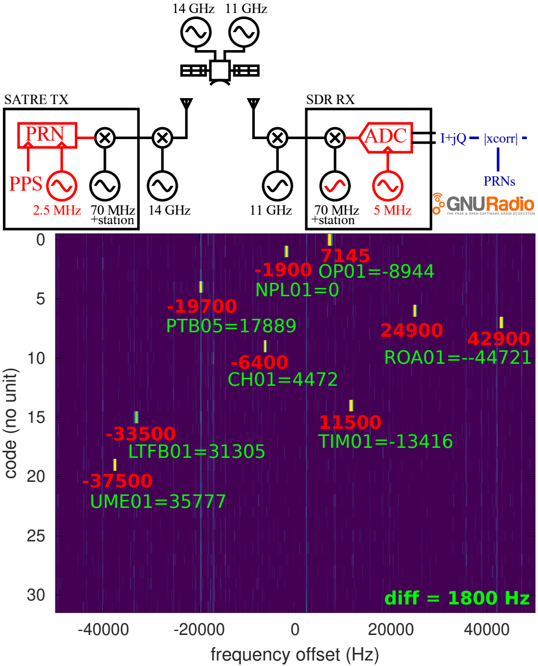


The Matlab code generates the right sequence but *not* starting with the same sequence than the C program

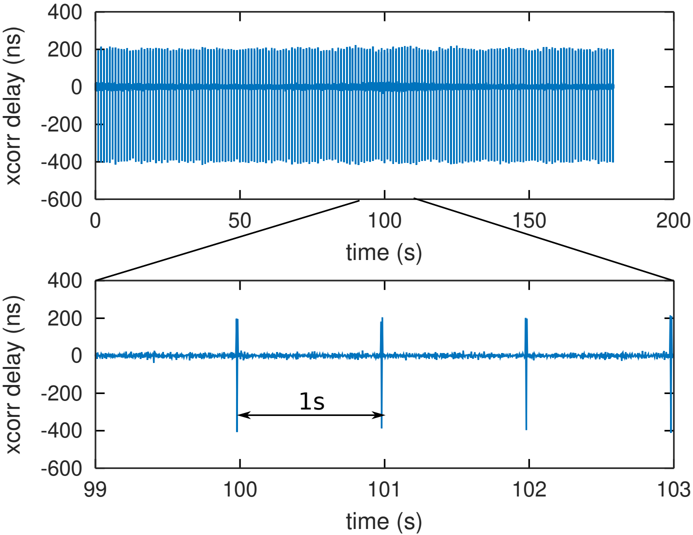
⇒ time offset but still at least 60% overlap despite truncation of the 14-bit sequence to 10000 chips

Processing sequence

1. coarse frequency offset by squaring the signal to get rid of BPSK: carrier offset at $2\delta\omega$
2. compensate for frequency offset by multiplying with $\exp(j\delta\omega t)$ with $t = [0 : N-1]/f_s$ (GNU Radio Costas Loop with order=2)
3. correlation with known pseudo random pattern interpolated by sampling rate/chip rate (=2 if $f_s = 5$ MHz)
4. linear fit of phase evolution and fine frequency offset correction ($xcorr(x, y \cdot \exp(j\varphi)) = \exp(j\varphi) \cdot xcorr(x, y)$)
5. atan(Q/I) provides π-rotation insensitive phase evolution (timestamp every 10000 chips @ $\underbrace{\text{2.5 Mchips/s}}_{\text{1st notch of FFT}}$ i.e. once every **4 ms**)
6. Process full 3 minute (3.6 GB file fitting in a 4-GB RAM Raspberry Pi4 ramdisk) recorded at 5 MS/s as 20000 sample-sequences making sure a single correlation peak is found at each iteration



1-PPS delay comparison



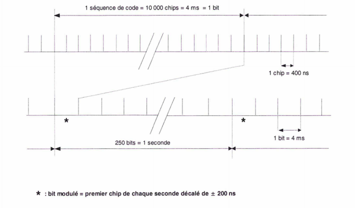
- coarse frequency offset from squaring the signal
- fine frequency offset from phase linear fit
- frequency must "only" be compensated for well enough to avoid wasting signal to noise ratio, but **no metrological** meaning
- second order polynomial fit of the correlation peak for sub-sampling period ($\ll$ 200 ns at 5 MS/s) resolution identification of correlation peak position
- 200 ns jumps of the correlation peak at beginning of each second

1-PPS mark in BPSK stream

Time-domain interpretation: ±200 ns (Merck, 2019 & Mitrex 2500A, 1989)

La fréquence d'horloge du registre à décalage étant de 2,5 MHz (voir les considérations précédentes), chaque chip dure 400 ns d'où une séquence binaire de durée 4 ms, reproduite 250 fois par seconde comme indiqué sur la figure A1.7. On remarque sur cette figure que le premier chip de chaque seconde est décalé de plus ou moins 200 ns. Ce décalage dans le temps a pour objectif de différencier chaque seconde (grâce à la détection de cet unique chip de durée rallongée ou raccourcie de 200 ns).

182 *Etude du fonctionnement du modem SATRE*



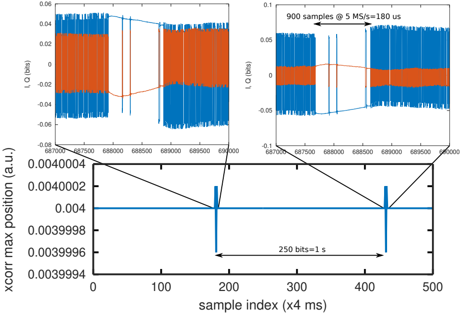
*** *Figure A1.7 : séquence de code pour un chip rate de 2,5 MChips/s* ***

Frequency-domain interpretation: ±90° (Hartl, 1986)

2.2 PN-Encoding/Decoding

As shown in fig. 1, MODEM 1 (2) is fed by the 5MHz (or 10MHz if desired) standard frequency of the cesium clock cl1 (cl2). The frequency is divided by a factor of two (or four) and used as the PN-clock (the description is true for MITREX 2500, the newer version. In the original MITREX, the clock rate was 2 MHz, and therefore a division of 2.5 or 5 resp. was necessary). This is also called the chiprate. In addition, the 1 pps time tick of cl1 (2) is used for the generation of the 1 sec period phase modulation of the PN-code. The PN-signal consists of "bits" of 10.000 chips and length of 4 msec. 249 such bits are sent before the bit 250 is to indicate the occurance of the 1 pps pulse. The indication is done by delaying the first 5000 chips of this bit 90 degrees and advancing the next 5000 chips by 90 degrees.

What we see (SATRE TX monitor) ...

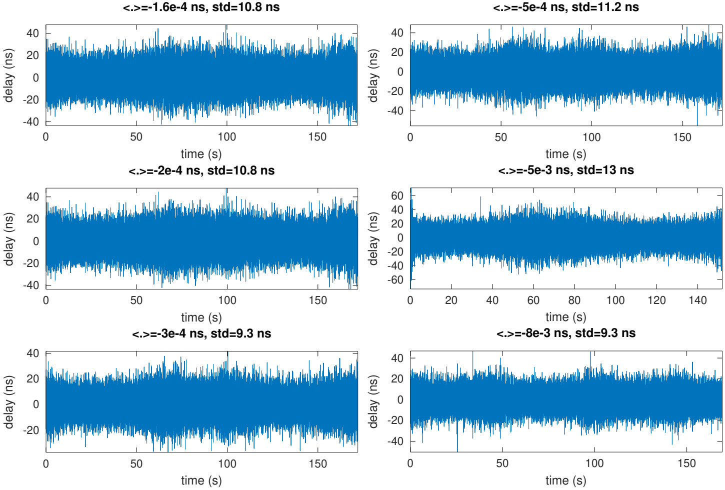


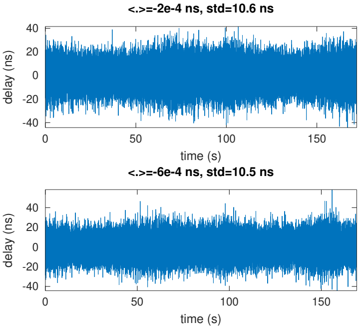
K. Imamura & F. Takahashi, *Frequency and Time Comparison – Two-way time transfer via a geostationary satellite*, J. of the Communication Research Laboratory **39**(1), 91–100 (1992)

(2) Transmission of 1PPS signal

The signal transmitted via a geostationary satellite has a delay of several hundred milliseconds. Because this delay is greater than the code length, the 4-ms ambiguities occur at the receiving site. To identify the accurate code for selection, the modulation of one of the 250 codes is synchronized with the in-house 1PPS signal. The method of the modulation is 1-chip delay of the M-sequence.

Correlation peak delay fluctuation for the various received signals (8 observatories recorded by SDR)

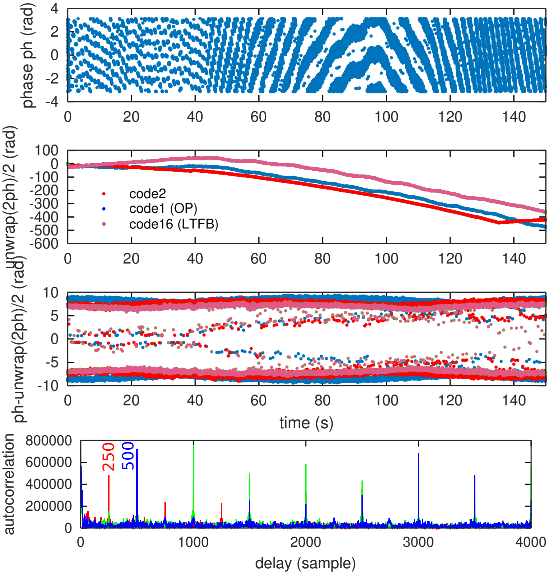




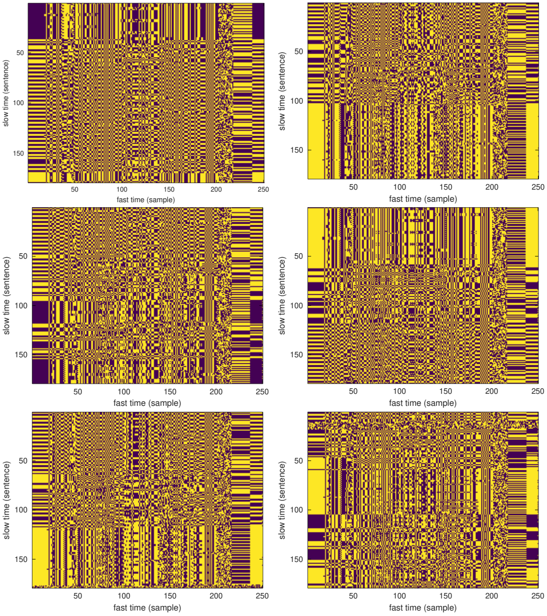
- **only correlation** maximum position (oversampled with parabola fitting) used to estimate time difference
- σ_{delay} $\simeq$9-10 ns over 3 minutes (removing the 200 ns jump every 1 s)

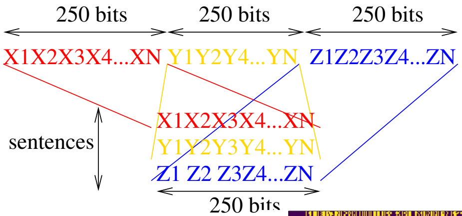
BPSK digital signal detection

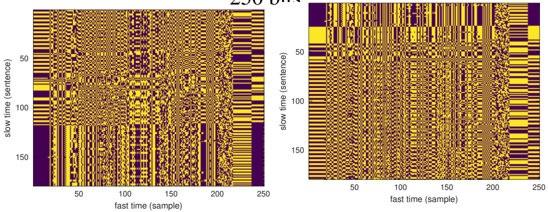
- Similar to GPS CDMA: XOR bits with code unique to each transmitter $\Rightarrow$ after correlating with known code, recover messages
- Phase varies due to the various uncontrolled oscillators
- $2\varphi = 0[2\pi]$ so $unwrap(2\varphi)/2$ provides phase drift
- $\Phi = \varphi - unwrap(\underbrace{2\varphi}_{0[2\pi]})/2$ for BPSK digital communication detection provides $+/-1 \in \mathbb{R}$ output
- $sign(\Phi)$ is the two possible bit states
- message repetition: autocorrelation every 250 (=1/4 ms) cross-correlation sample=1 s

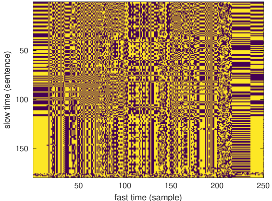


SATRE time dissemination code





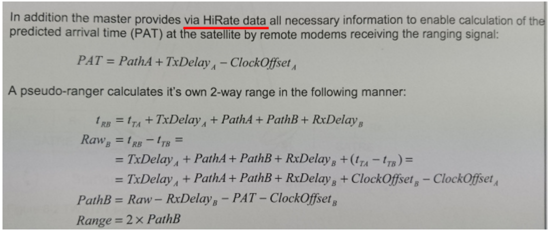




- Codes 0, 15, 16, 1, 2, 4, 7, 8, 5
- No mention of digital communication layer in K. Imamura & F. Takahashi, *Frequency and Time Comparison – Two-way time transfer via a geostationary satellite*, J. of the Communication Research Laboratory **39**(1), 91–100 (1992): added in SATRE?

SATRE time dissemination code

Carrier recovered by unwrapping $2d\varphi \in [0:2\pi] = 0[2\pi]$ and exctract $arg(\varphi - d\varphi))$



In addition the master provides via HiRate data all necessary information to enable calculation of the predicted arrival time (PAT) at the satellite by remote modems receiving the ranging signal:

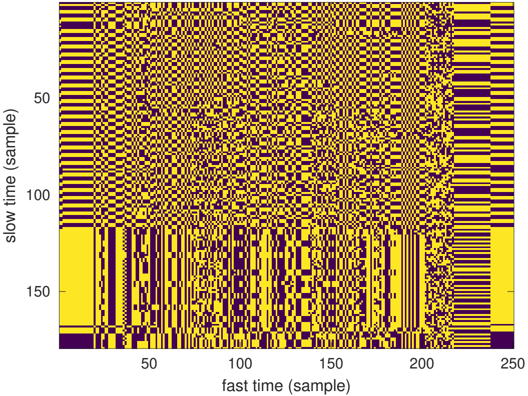
$$PAT = PathA + TxDelay_A - ClockOffset_A$$

A pseudo-ranger calculates it's own 2-way range in the following manner:

$$t_{RB} = t_{TA} + TxDelay_A + PathA + PathB + RxDelay_B$$
$$Raw_B = t_{RB} - t_{TB} =$$
$$= TxDelay_A + PathA + PathB + RxDelay_B + (t_{TA} - t_{TB}) =$$
$$= TxDelay_A + PathA + PathB + RxDelay_B + ClockOffset_B - ClockOffset_A$$
$$PathB = Raw - RxDelay_B - PAT - ClockOffset_B$$
$$Range = 2 \times PathB$$

Coding scheme of the timing message? `https://github.com/BatchDrake/cccrack` [a] cannot identify convolutional forward error correction mechanism.

[a]M. Marazin, R. Gautier, G. Burel, *Dual Code Method for Blind Identification of Convolutional Encoder for Cognitive Radio Receiver Design*, Proc IEEE GLOBECOM Workshops (2009)



The content and coding scheme of the digital communication layer [a] are not documented

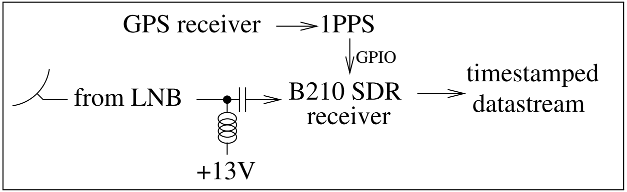
[a]B. Seeber, *SDR Tips and Tricks*, DEFCON 24 Wireless Village (2016), at 17:40 of `https://www.youtube.com/watch?v=yZ5G0nYSM98`

Why TWSTFT?

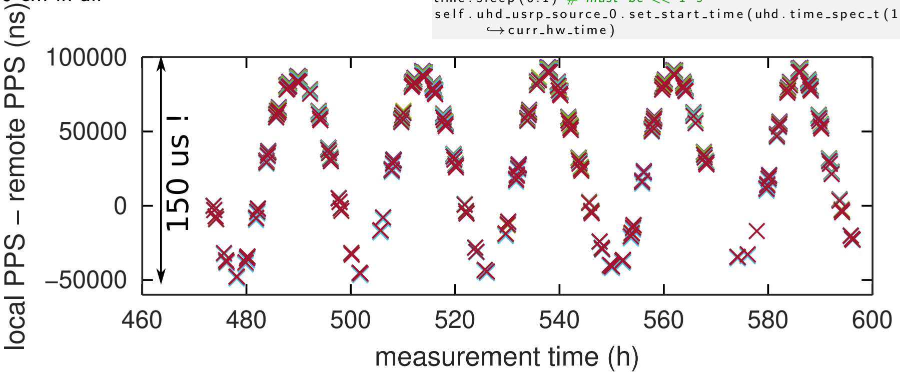
Time transfer requirements:

MiFID II financial transactions	100 μs
GPS C/A	100 ns
GPS phase	1[a] ns
TAI	$\ll$1 ns

[a] 1 ns=30 cm in air



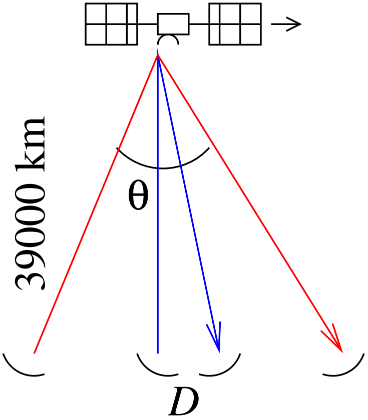

```
self.connect((self.blocks_head_0, 0), (self.blocks_file_sink_0, 0))
self.connect((self.uhd_usrp_source_0, 0), (self.blocks_head_0, 0))
# add external 1-PPS trigger:
curr_hw_time = self.uhd_usrp_source_0.get_time_last_pps()
self.uhd_usrp_source_0.set_time_next_pps( uhd.time_spec_t(0.5) + →
    ↪curr_hw_time)
time.sleep(0.1) # must be << 1 s
self.uhd_usrp_source_0.set_start_time(uhd.time_spec_t(1.01) + →
    ↪curr_hw_time)
```



Challenge of one-way reception: multiple antennas

A geostationnary satellite is not fixed in space but subject to gravitational forces (Moon, Sun)
$\Rightarrow$ need to recover satellite attitude

- A geostationnary satellite moves in a sphere 30-km radius around its expected location
- 30 km=100 μs: can we detect and compensate for satellite motion using multiple antennas?
- 30 km at 39000 km means angle of arrival variation of $d\vartheta = 7.7 \cdot 10^{-4}$ rad
- $\varphi = \vec{k}\vec{r} = \frac{2\pi}{\lambda} \cdot D \cdot \cos(\vartheta) \Rightarrow d\varphi = \frac{2\pi}{\lambda} \cdot D \cdot \sin(d\vartheta) \simeq \frac{2\pi}{\lambda} \cdot D \cdot (d\vartheta)$: if D distance between antennas is 3 m, then $\varphi = 0.26$ rad at 5.5 cm wavelength or 185 ps period$\rightarrow$ delay variation of 8 ps

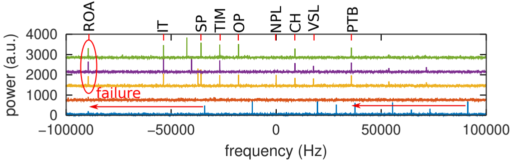


Impossible with an array of local parabolic antenna: time delay measurement accuracy in the 100 ps range

But what if $D = 1500$ km? Then the delay variation becomes 3.9 μs !

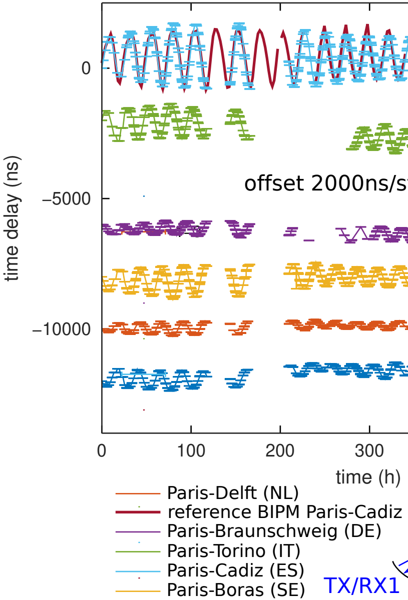
Challenge of one-way reception: single antenna observations

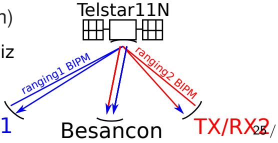
- Use spatial diversity of signal sources: observatories disseminated all over Europe
- Varying LO & transponder frequency offset ⇒ set freq. offset by identifying the lowest carrier



- For each pair of observatories (different illumination angles) measure difference of 1-PPS time of arrival
- Each observatory emits during different timeslots (SATRE can only acquire a single pair) when SDR analyzes the signal from all emitters ⇒ interpolate
- Single antenna reception compares nicely with BIPM dataset [a]

$$observation = \frac{1}{2}\left(ranging_1 - ranging_2\right)$$





[a] Data shared between observatories: `https://webtai.bipm.org/ftp/pub/tai/data/2022/time_transfer/twstft/`

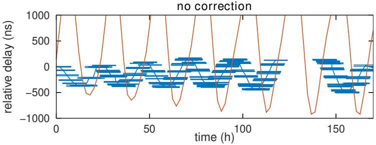
Problem of absolute ranging

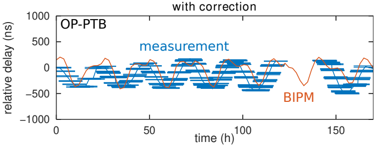
Good **fluctuation** agreement after **interpolation** (SATRE) but mean value mismatch ($x2$)

PTB_1	001900	0.264554333125
OP	020700	0.262389215515
PTB_2	021900	0.264564294602

$\Rightarrow$ PTB=$PTB_2 - \frac{12}{120}(PTB_2\text{-}PTB_1)$

$\overline{\frac{1}{2}(\text{OP-PTB})} = 0.912_5$ ms v.s $\overline{\Delta 1 \text{ PPS}} = 1.825$ ms

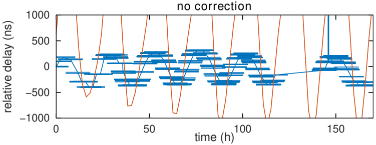


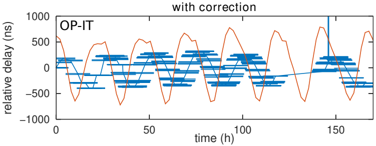


IT_1	002500	0.262539315944
OP	020700	0.262389215515
IT_2	022500	0.262548959052

$\Rightarrow$ IT=$IT_2 - \frac{18}{120}(IT_2\text{-}IT_1)$

$\overline{\frac{1}{2}(\text{OP-IT})} = 1.920_9$ ms v.s $\overline{\Delta 1 \text{ PPS}} = 3.841$ ms





Problem: short pulse repetition interval of SATRE (4 ms) makes the measurement ambiguous: $\longrightarrow$

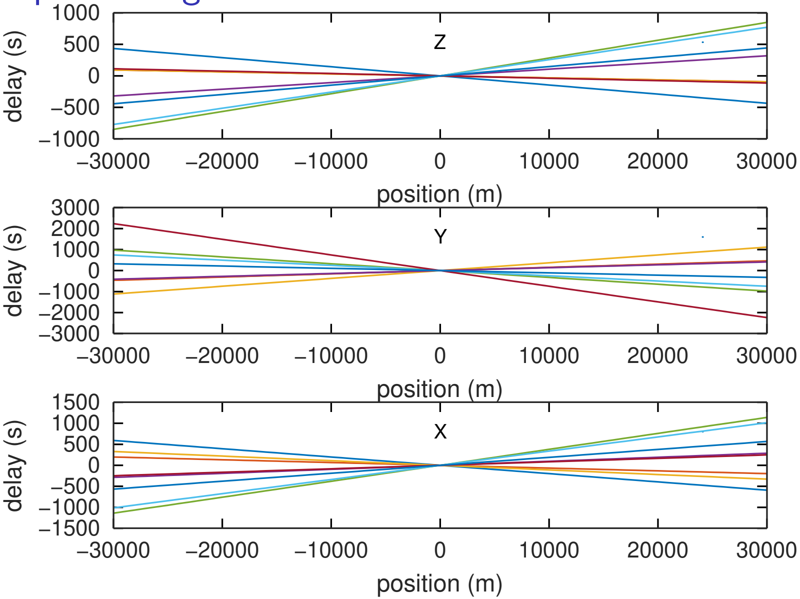
Observatory	lat (deg)	lon (deg)	angle (deg)	delay (ms)
OP	48.84	2.34	59.645	262.23
LTFB	47.25	5.99	60.497	262.82
Greenwich	51.48	0	60.390	262.74
INRIM	45.02	7.64	60.092	262.54
PTB	52.3	10.46	65.826	**266.56**
SW Spain	36	-9	44.685	252.70
NW Finland	68	42	86.086	281.41

OP ranging 0.262324478570 s
ROA ranging 0.258119759893 s
Difference 4.2 ms> 4 ms

$$\frac{1}{2}(\text{Paris} - \text{Cadiz}) = 2.1024 \text{ ms}[2\text{ms}] = 102.4\ \mu s$$

Challenge of one-way reception: single antenna simulations

- single antenna measurement **cannot** compensate for tropospheric and ionospheric delay from satellite to receiver
- satellite motion can be deduced knowing the observatory location and satellite latitude
- more observations (≥ 6 observatories) than variables (3) $\Rightarrow$ least square solution with residual
- position fluctuation **around equilibrium** only requires projecting satellite motion vector on satellite-observatory vector $\rightarrow$
- impact of satellite motion on time of flight **difference** reduced due to nearly identical identical line of sight from Western Europe to Telstar11N



Error function

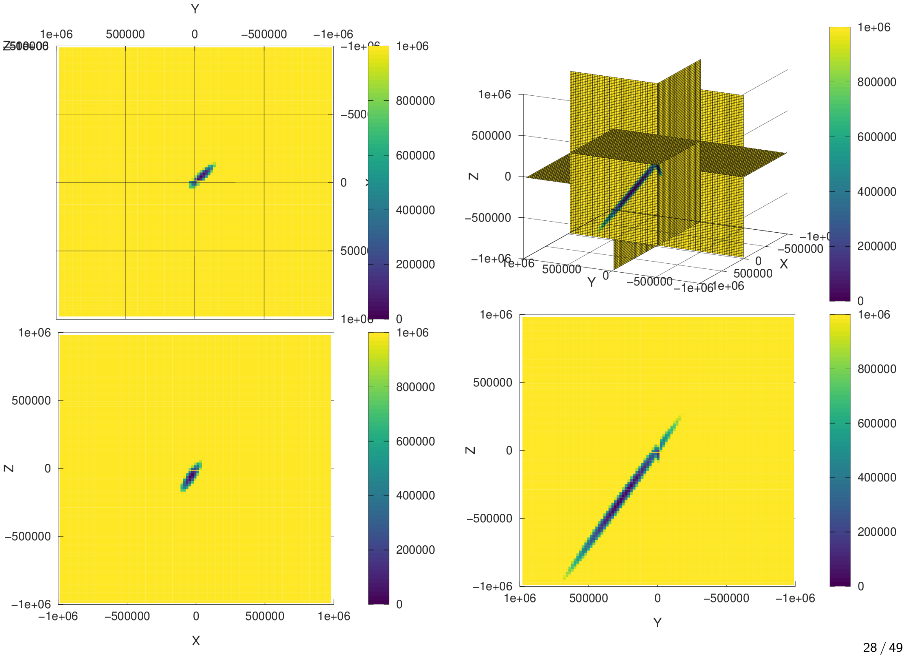
$$\varepsilon = \sum_i (d_i/c - t_i)^2$$

Objective:

$$min(\varepsilon(d_i))(x, y, z)$$

for satellite position (x, y, z)

OP-SP @ 86.641 ns
OP-IT @ 343.285 ns
OP-ROA @ -485.357 ns



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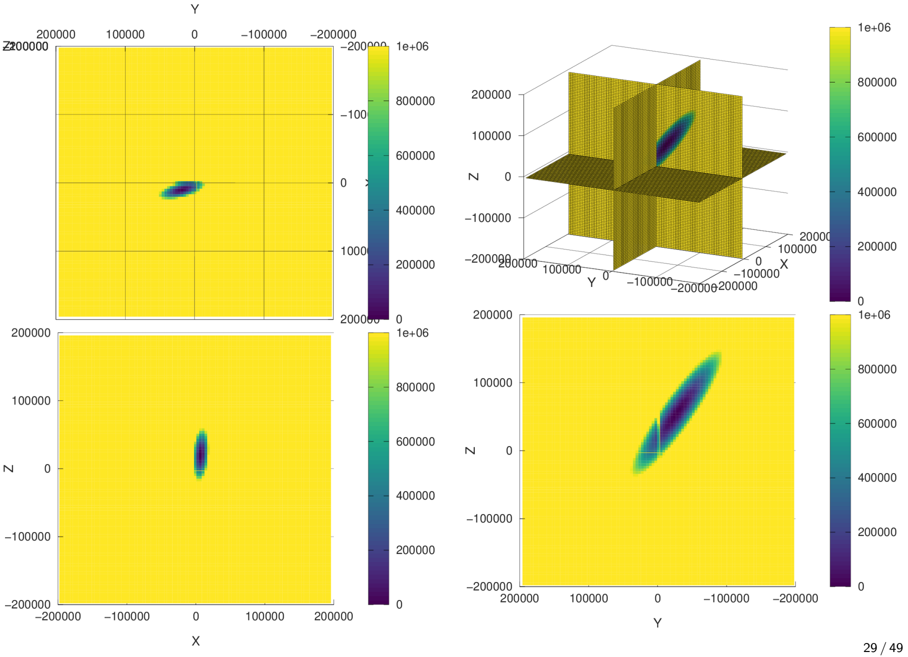
OP-SP @ 86.641 ns
OP-IT @ 343.285 ns
OP-ROA @ -485.357 ns
OP-NPL @ -224.806 ns
OP-VSL @ -59.948 ns
OP-PTB @ 244.319 ns



Error function

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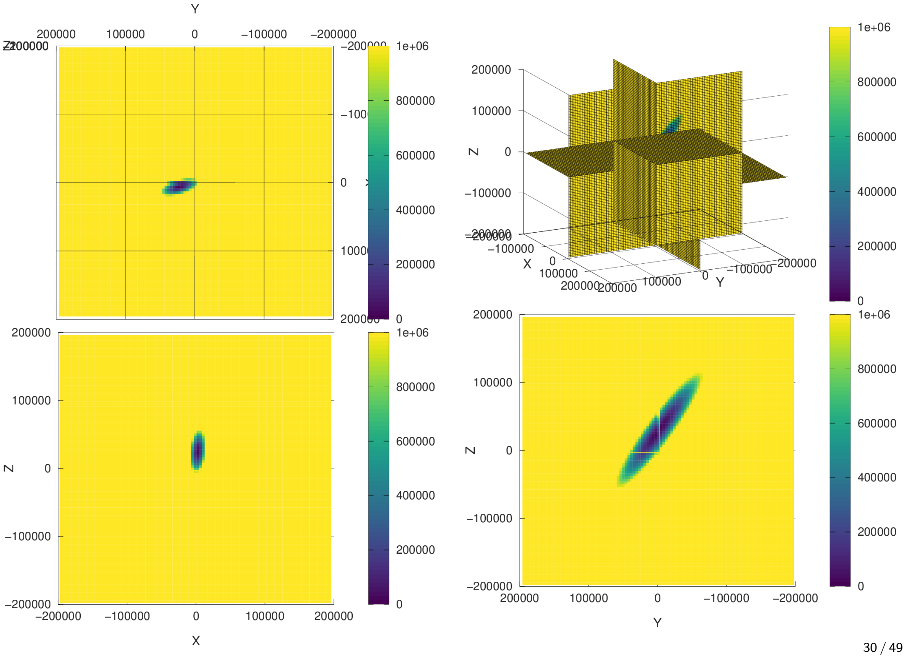
Objective:

$$min(\varepsilon(d_i))(x, y, z)$$

for satellite position (x, y, z)

OP-SP @ -70.534 ns
OP-IT @ 548.516 ns
OP-ROA @ -184.947 ns
OP-NPL @ -335.514 ns
OP-VSL @ -198.028 ns
OP-PTB @ 244.825 ns



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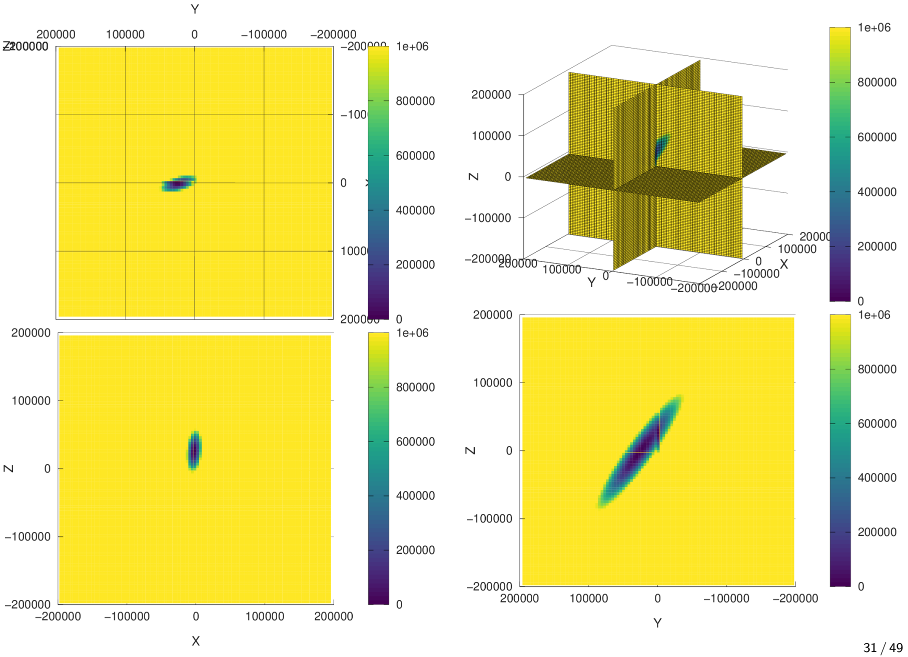
OP-SP @ -263.626 ns
OP-IT @ 704.868 ns
OP-ROA @ 197.608 ns
OP-NPL @ -445.955 ns
OP-VSL @ -151.232 ns
OP-PTB @ 175.705 ns



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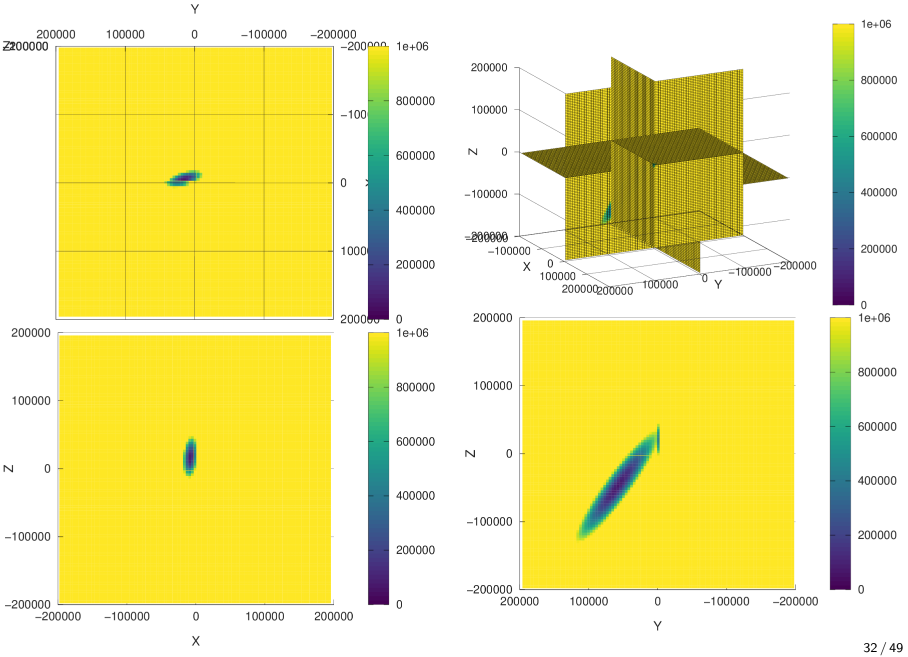
OP-VSL @ . ns
OP-PTB @ . ns



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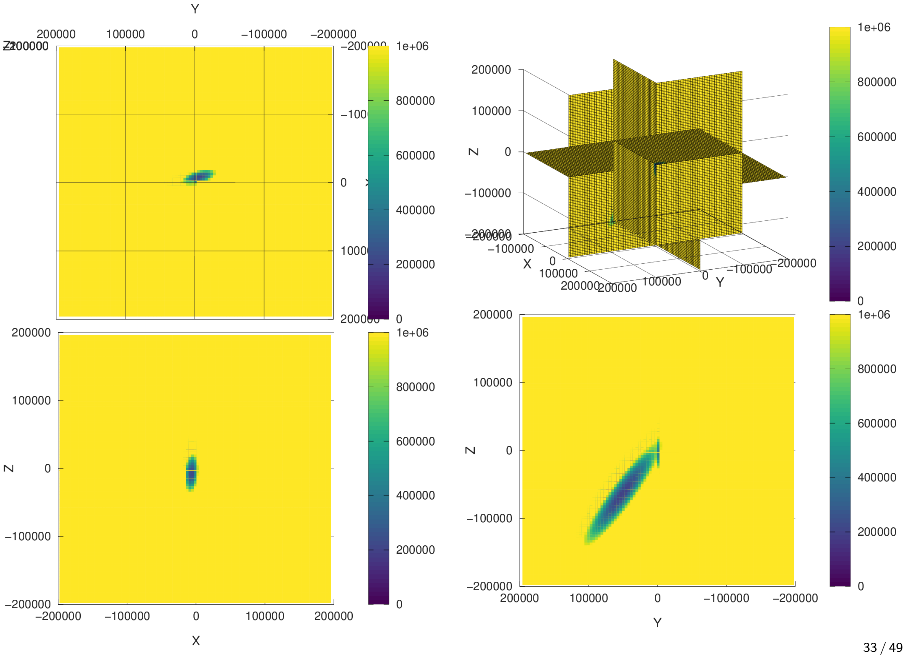
OP-PTB @ . ns



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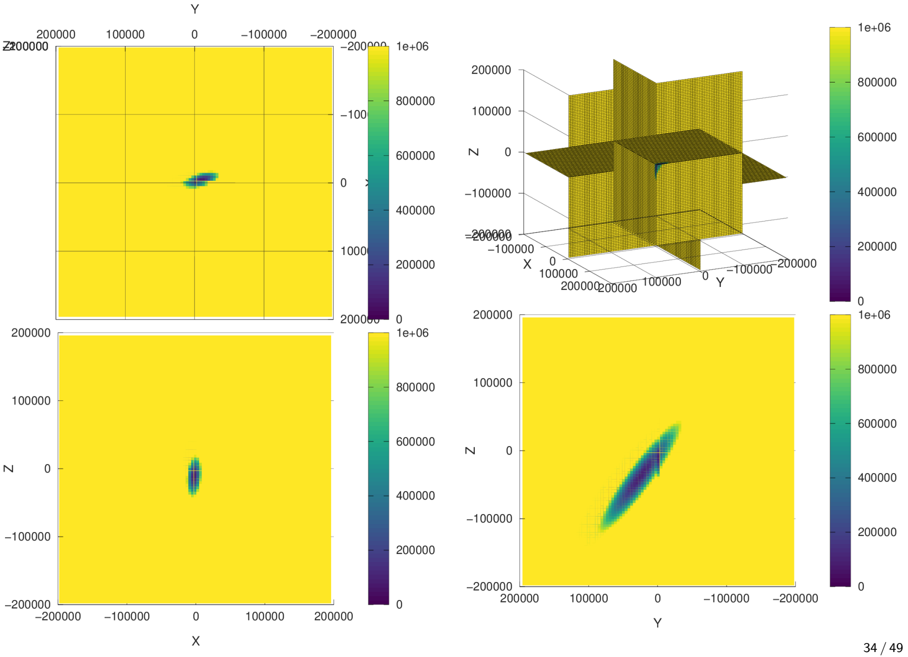

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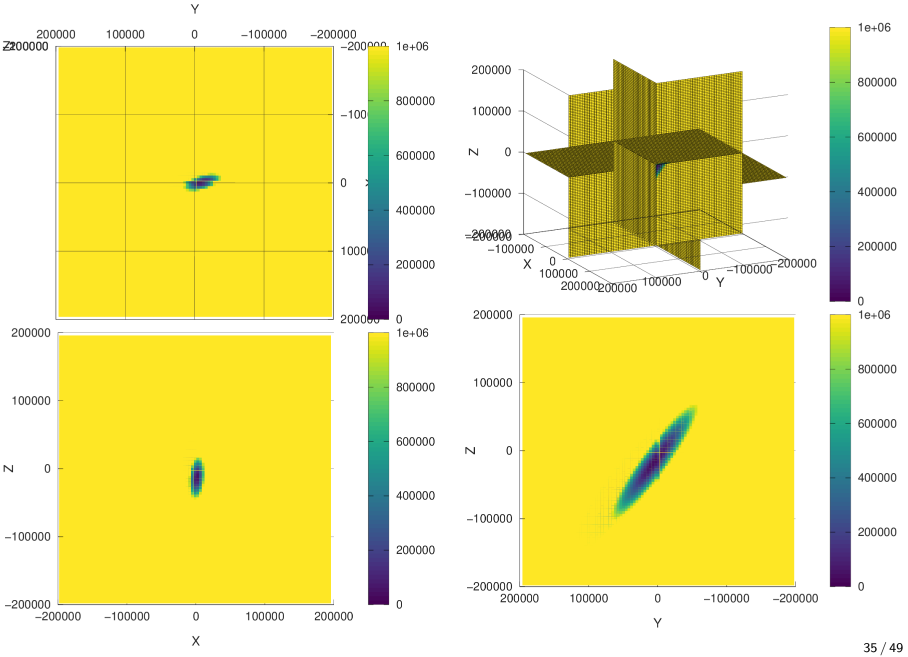

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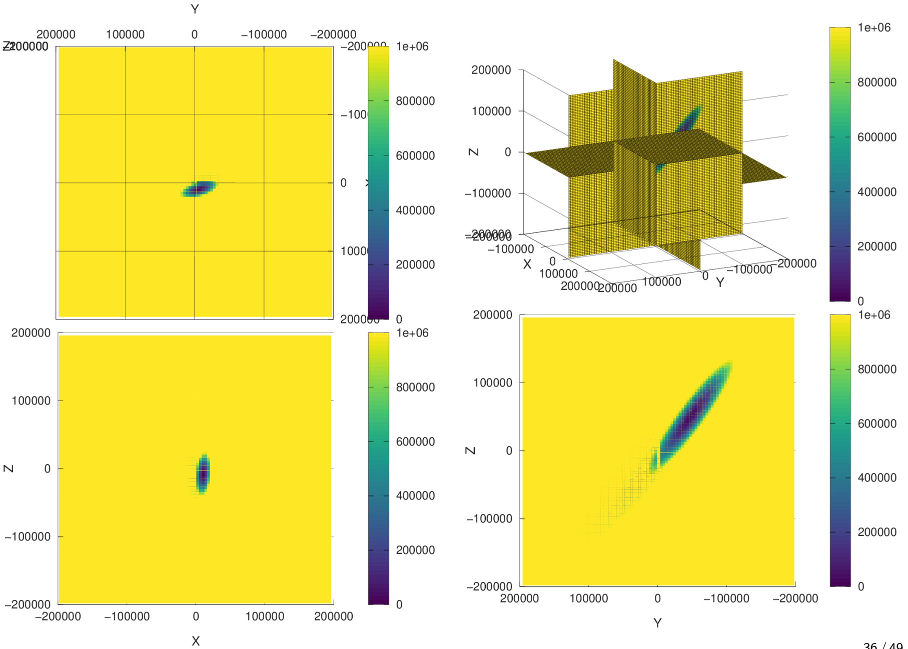

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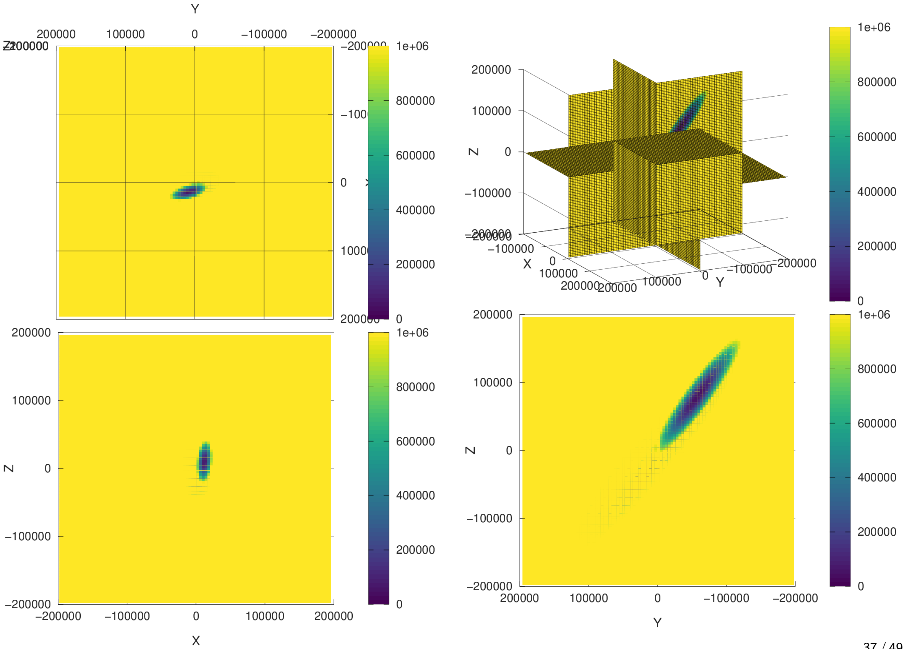

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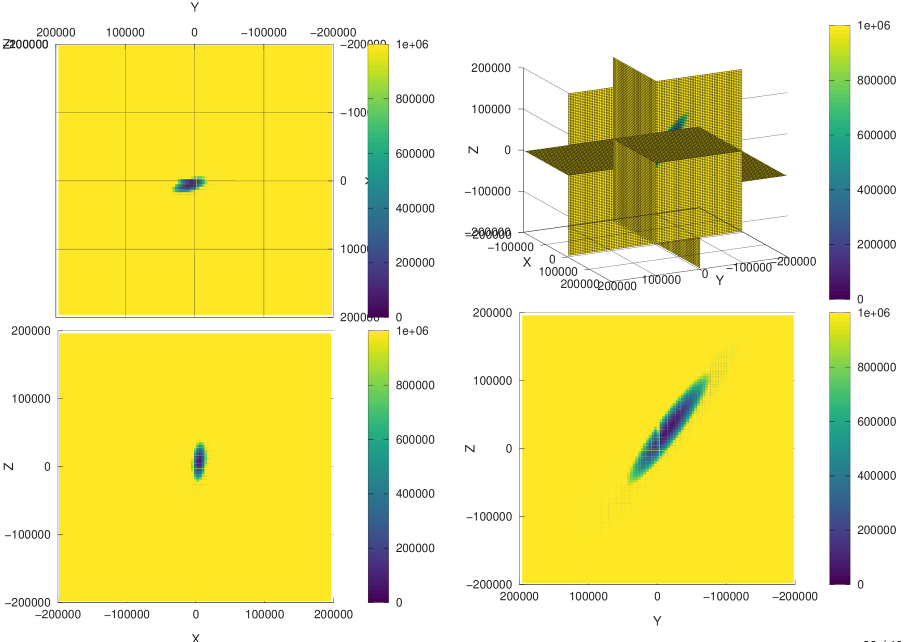

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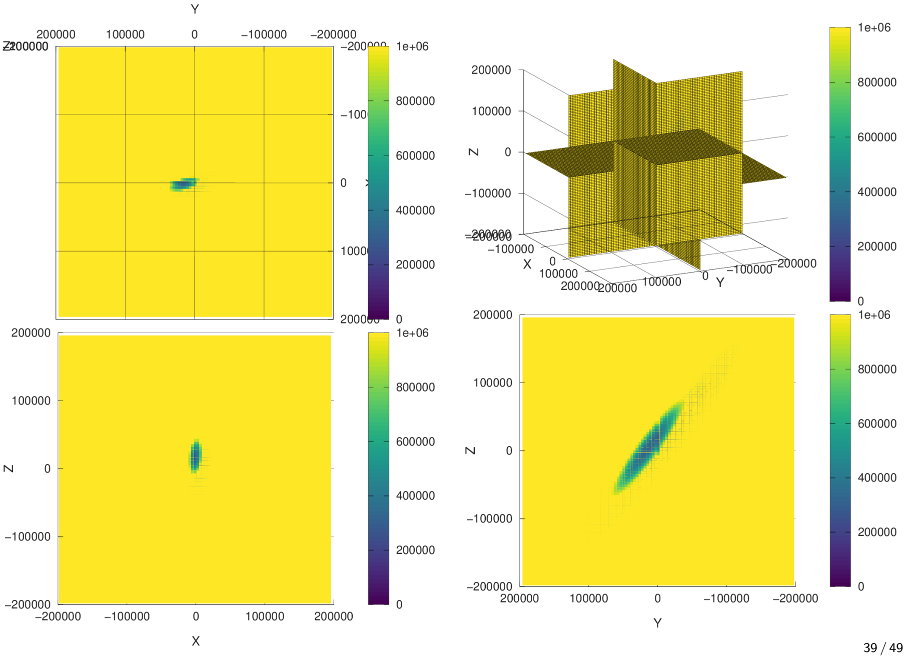

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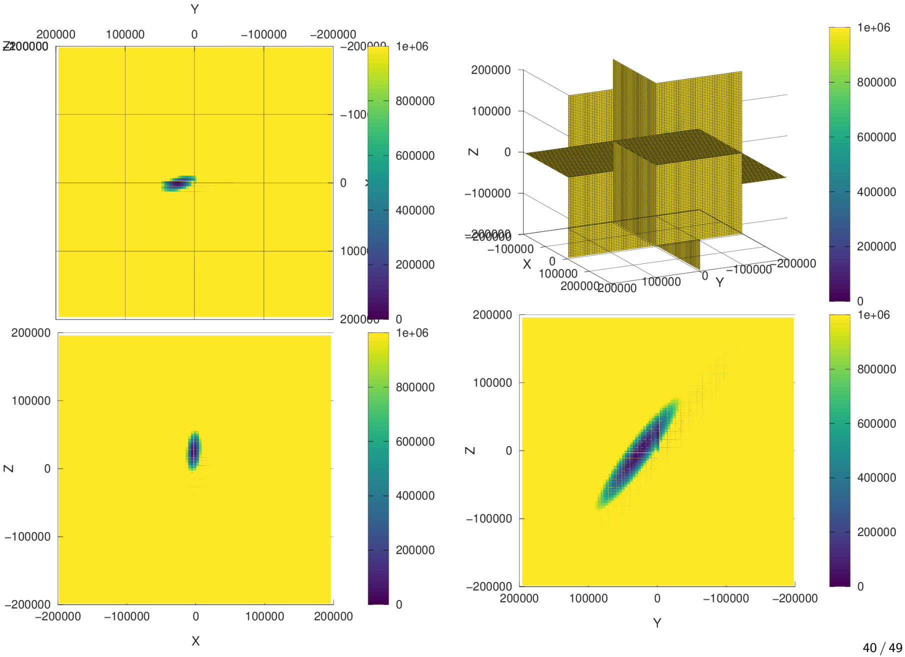

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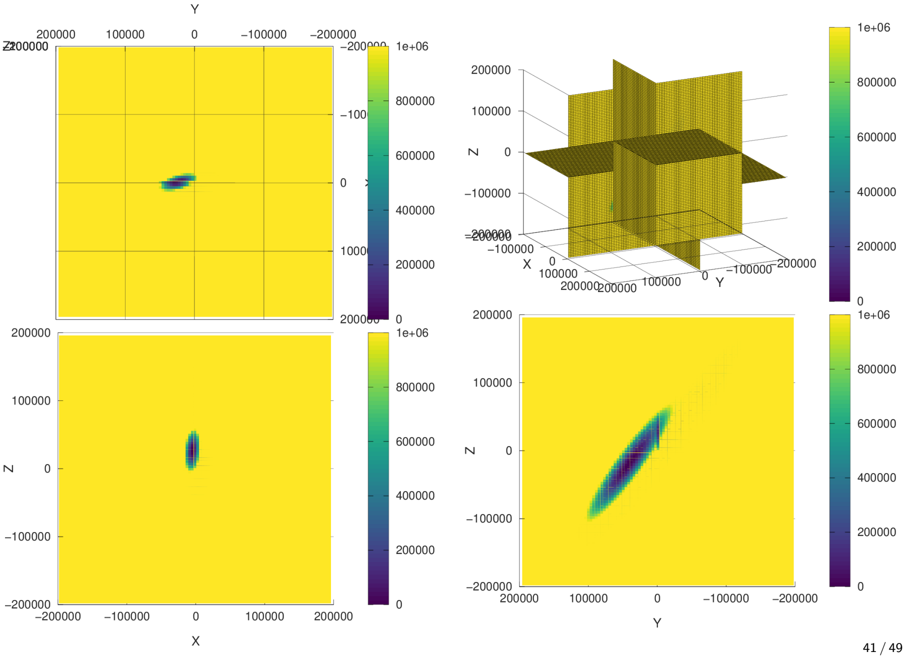
OP-PTB @ . ns



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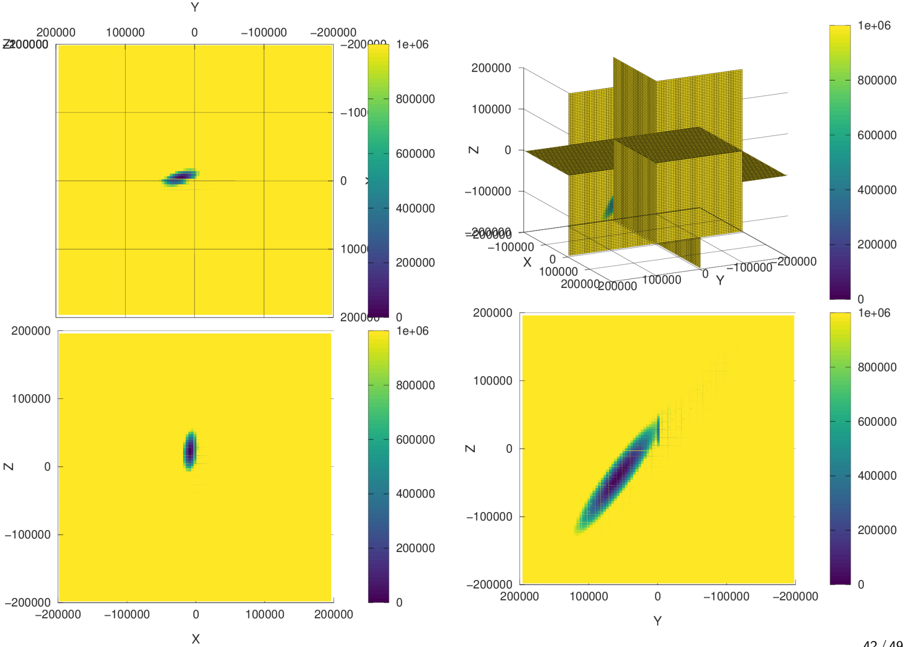
OP-PTB @ . ns



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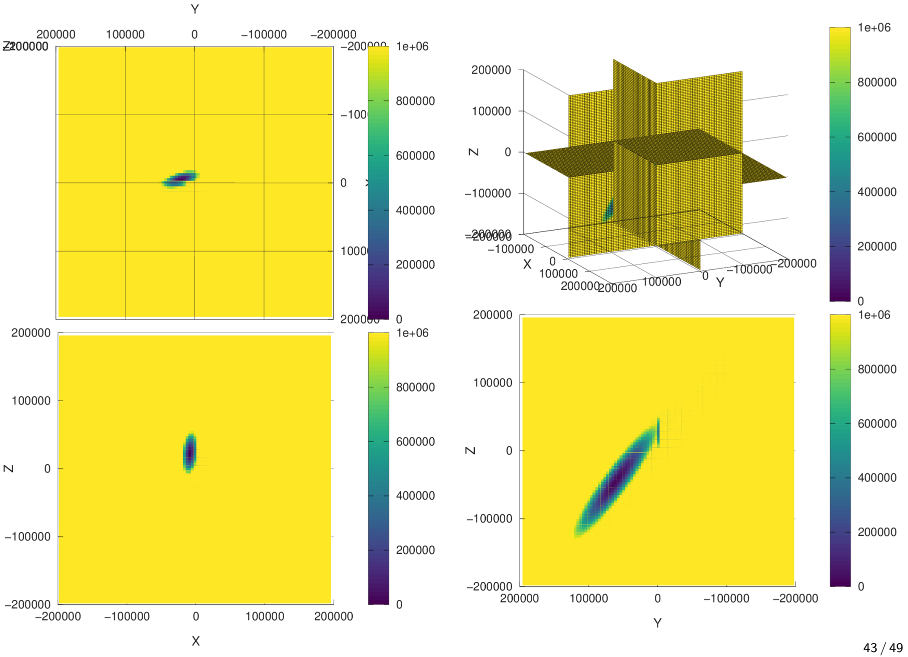

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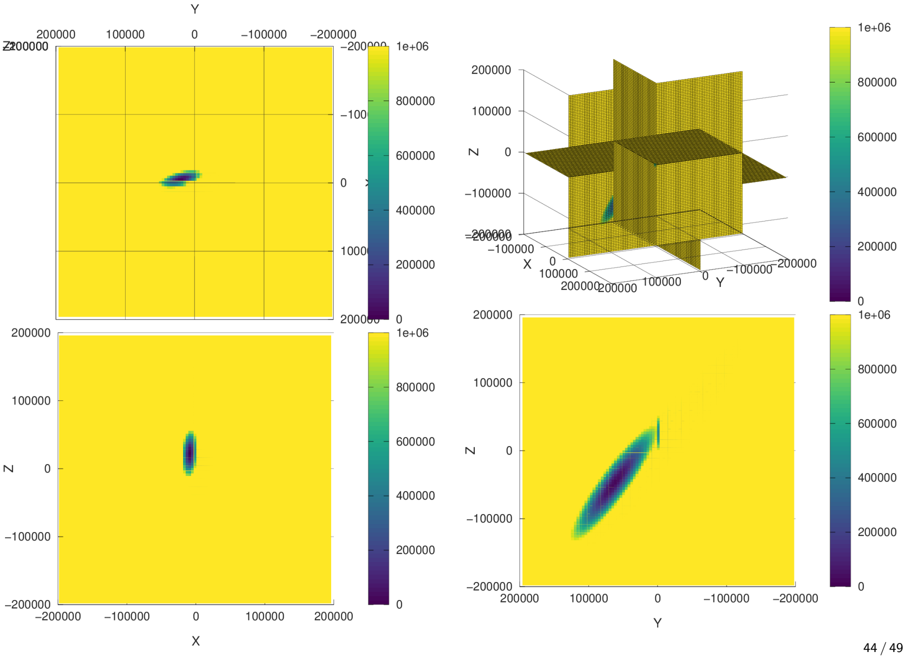

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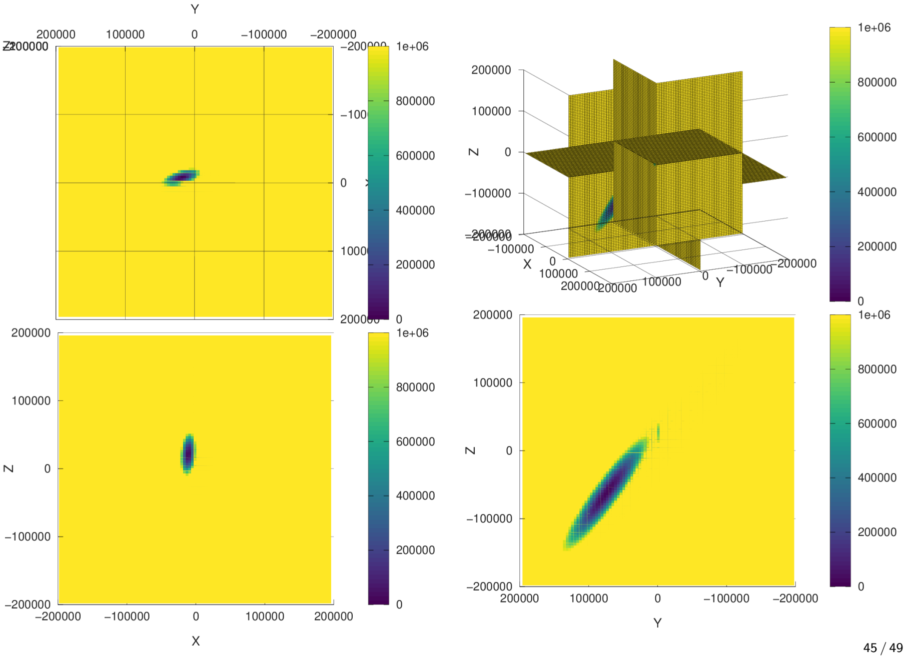
OP-NPL @ . ns
OP-VSL @ . ns
OP-PTB @ . ns



Error function

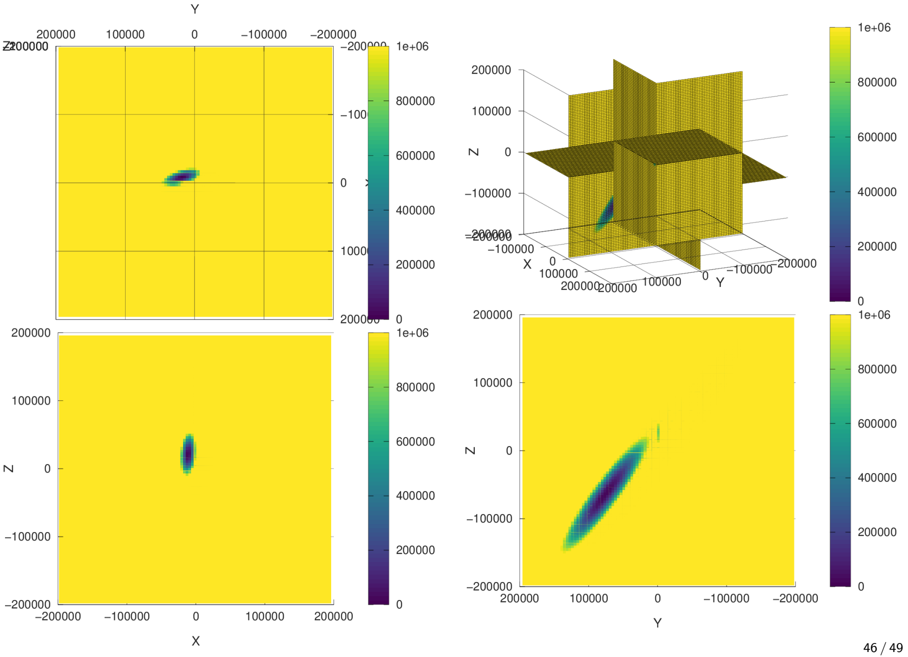
$$\varepsilon = \sum_i (d_i/c - t_i)^2$$

Objective:

$$min(\varepsilon(d_i))(x, y, z)$$

for satellite position (x, y, z)

OP-SP @ . ns
OP-IT @ . ns
OP-ROA @ . ns
OP-NPL @ . ns
OP-VSL @ . ns
OP-PTB @ . ns



Error function

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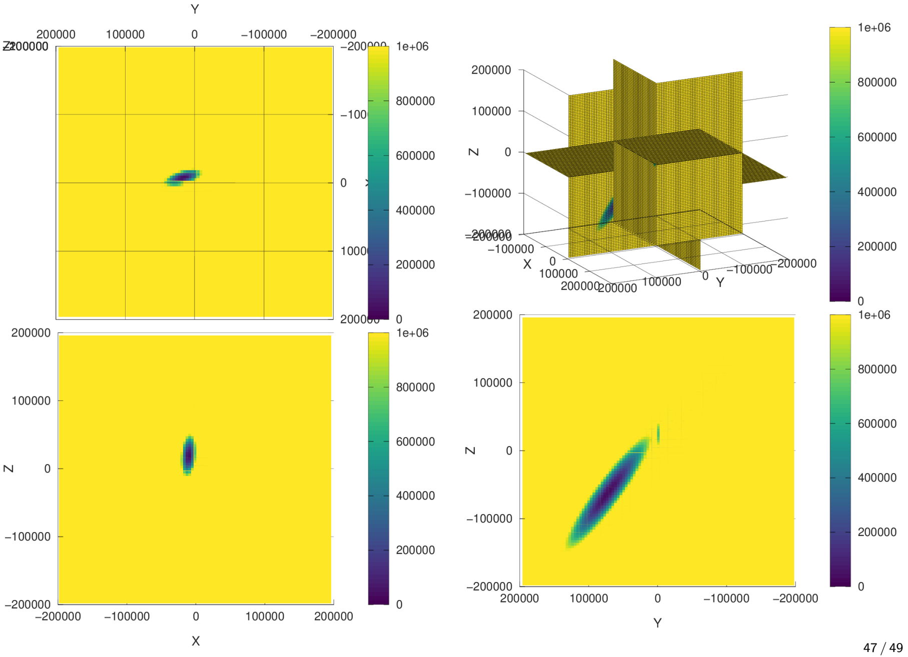
OP-PTB @ . ns



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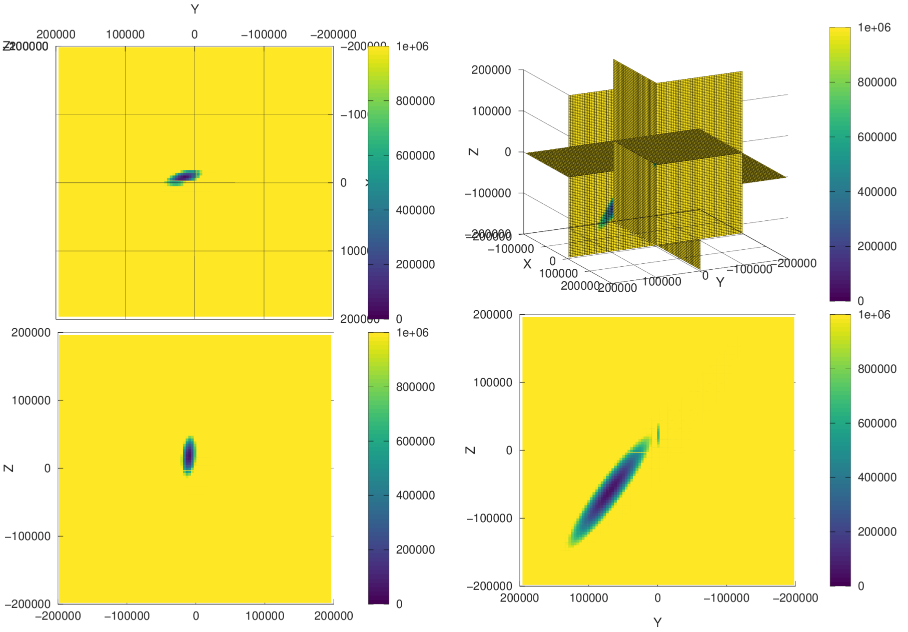

Conclusion

- Ability to receive TWSTFT with a satellite-TV reception antenna
- Processing framework for extracting timing information from European observatories

`https://github.com/oscimp/gr-satre`

- Possible complement to GPS time dissemination if satellite motion compensation is achieved
- Generic framework using COTS hardware for synchronizing oscillators in the $10^{-9}\tau^{-1/2}$ range [a]
- In progress: better least-square fitting initialization + bounded solution space + Kalman filter
- In progress: Sagnac effect correction?
- Digital communication decoding

[a] $\sigma_\tau \simeq 1$ ns @ 1 s

Challenge of satellite position estimate/prediction: NORAD's Two-Line Element description is poorly suited for geostationay satellite orbit description [a] [b]
"The maximum accuracy for a TLE is limited by the number of decimal places in each field. In general, TLE data is accurate to about a kilometer or so at epoch and it quickly degrades.
...
Expect a satellite's orbit to constantly change as the SGP4 propagation routine models effects like atmospheric drag and the Moon's gravity. In particular, the true anomaly parameter can swing wildly for satellites with nearly circular orbits, because the reference point from which true anomaly is measured — the satellite's perigee — can be moved by even slight perturbations to the orbit "

[a] `https://rhodesmill.org/skyfield/earth-satellites.html`

[b] D.A. Vallado, P. Crawford, R. Hujsak, T.S. Kelso, *Revisiting Spacetrack Report #3: Rev 3*, Proc. AIAA/AAS Astrodynamics Specialist Conference (2006) at `https://celestrak.org/publications/AIAA/2006-6753/AIAA-2006-6753-Rev3.pdf`

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