CENTRE NATIONAL D'ÉTUDES SPATIALES

Processing of DORIS RINEX data and relationship with the “2.2” format

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- DORIS RINEX format overview
- Measurement model
- Relationship with to 2.2 format

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DORIS RINEX format overview

- Available for DGXX instruments tracking data
  - Jason-2 , Cryos-2
- These instruments deliver synchronous dual frequency phase and pseudo-range measurements (on seven simultaneous channels)
- Rinex format description available at

  ftp://ftp.ids-doris.org/pub/ids/data/RINEX_DORIS.pdf
- F. Mercier et al. , “Jason-2 DORIS phase measurement processing” , ASR, 2010

HEADER RECORD, ex: ja2rx11081.001

- **Receiver information**
- **Observables**
- **Scale factor**

```
      3.00           0                   D                   RINEX VERSION / TYPE
Expert               CNES                20110323 071127 UTC PGM / RUN BY / DATE
G = GPS R = GLONASS E = GALILEO S = GEO M = MIXED D = DORIS COMMENT
JASON-2                                                      SATELLITE NAME
2008-032A                                                    COSPAR NUMBER
STILO                CNES                                    OBSERVER / AGENCY
CHAIN1               DGXX                1.00                REC # / TYPE / VERS
DORIS                STAREC                                  ANT # / TYPE
        1.1940        -0.5980         1.0220                 APPROX POSITION XYZ
        0.9768         0.0001         0.0011                 CENTER OF MASS: XYZ
D   10  L1  L2  C1  C2  W1  W2  F   P   T   H                SYS / # / OBS TYPES
  2011    03    22    00    00   28.8553281     DOR          TIME OF FIRST OBS
D  100    2  C1  C2                                          SYS / SCALE FACTOR
D               1.900                                        L2 / L1 DATE OFFSET
    49                                                       # OF STATIONS
D01  BADB BADARY                         12338S002  3   0    STATION REFERENCE
D02  COBB COLD BAY                       49804S004  3   0    STATION REFERENCE
```

- **Table of ground beacons**
  - Correspondence between internal Rinex identifier and DORIS beacon name
  - Frequency shift factor

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- **Frequency shifted beacons**
- **Time reference beacons**

PAUB
KRWB
TLSB
HBMB

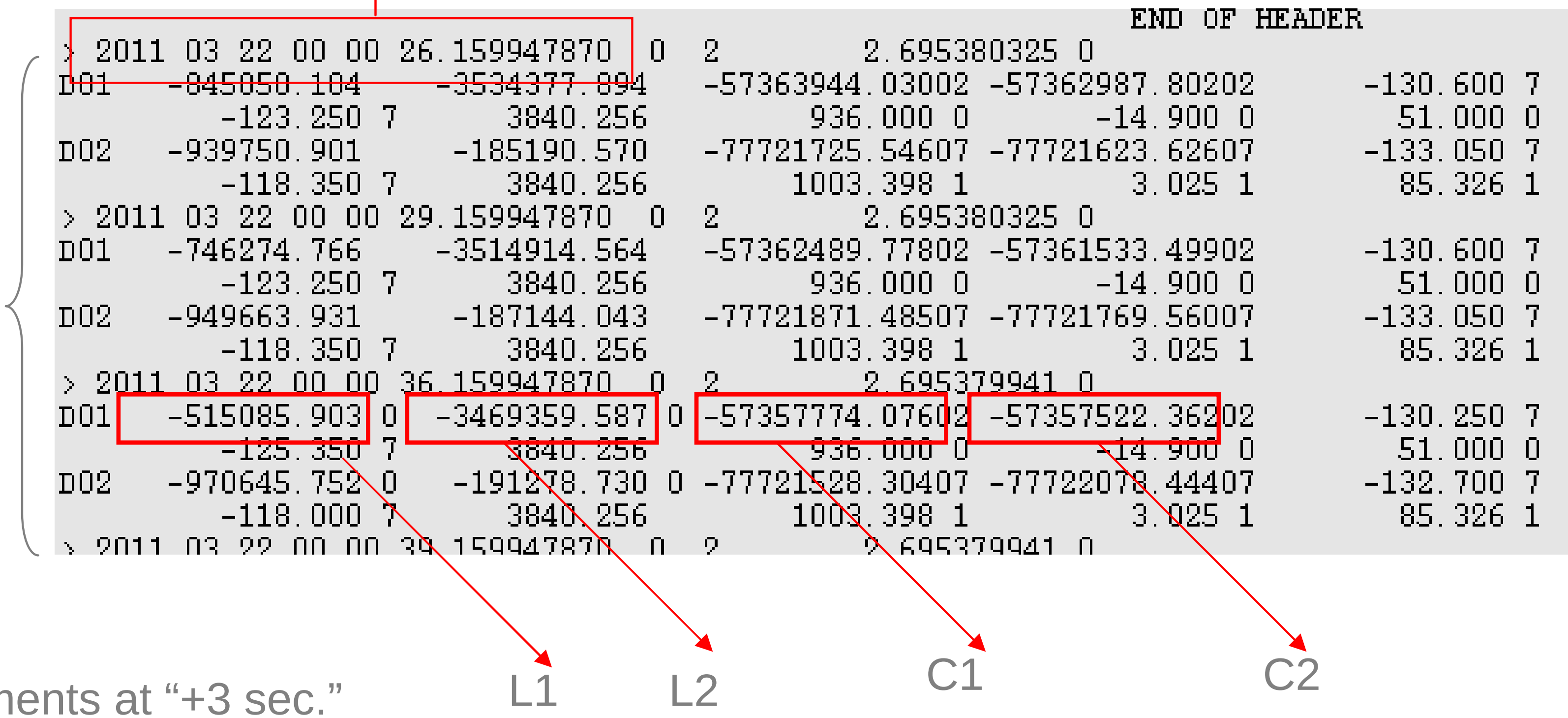
```
D17  PDMB PONTA DELGADA          31906S002  3   0    STATION REFERENCE
D18  TLSB TOULOUSE               10003S005  3   0    STATION REFERENCE
D19  GR3B GRASSE                 10002S018  3 -15    STATION REFERENCE
D20  GAVB GAVDOS                 12618S001  3  18    STATION REFERENCE
D21  DIOB DIONYSOS               12602S012  3   0    STATION REFERENCE
D22  METB METSAHOVI              10503S015  3   0    STATION REFERENCE
D23  REZB REYKJAVIK              10202S003  3   0    STATION REFERENCE
D24  SPJB NY-ALESUND             10317S005  3   0    STATION REFERENCE
D25  KRBB KRASNOYARSK            12349S002  3   0    STATION REFERENCE
D26  KIUB KITAB                  12334S006  3   0    STATION REFERENCE
D27  JIUB JIUFENG                21602S005  3   0    STATION REFERENCE
D28  MSPB MOUNT STROMLO          50119S004  3   0    STATION REFERENCE
D29  ARFB AREQUIPA               42202S007  3   0    STATION REFERENCE
D30  STJB ST JOHN'S              40101S002  3   0    STATION REFERENCE
D31  THUB THULE                  43001S005  3   0    STATION REFERENCE
D32  EVEB EVEREST                21501S001  3   0    STATION REFERENCE
D33  CIDB CIBINONG               23101S003  3   0    STATION REFERENCE
D34  YASB YARAGADEE              50107S011  3   0    STATION REFERENCE
D35  MIAB MIAMI                  49914S003  3   0    STATION REFERENCE
D36  GREB GREENBELT              40451S176  3   0    STATION REFERENCE
D37  MALB MALE                   22901S002  3   0    STATION REFERENCE
D38  AMVB AMSTERDAM              91401S005  3   0    STATION REFERENCE
D39  KETB KERGUELEN              91201S005  3   0    STATION REFERENCE
D40  RILB RIKITEA                92301S003  3   0    STATION REFERENCE
D41  YEMB YELLOWKNIFE            40127S009  3   0    STATION REFERENCE
D42  DJIB DJIBOUTI               39901S003  3   0    STATION REFERENCE
D43  MAHB MAHE                   39801S005  3   0    STATION REFERENCE
D44  REUB LA REUNION             97401S002  3   0    STATION REFERENCE
D45  CRQB CROZET                 91301S003  3   0    STATION REFERENCE
D46  MATB MARION ISLAND          30313S003  3   0    STATION REFERENCE
D47  SYPB SYOWA                  66006S003  3   0    STATION REFERENCE
D48  HBMB HARTEBEESTHOEK         30302S008  3   0    STATION REFERENCE
D49  NOWB NOUMEA                 92701S003  3   0    STATION REFERENCE
     4                                               # TIME REF STATIONS
D06           10.570        22.250                   TIME REF STATION
D15            0.019       -12.598                   TIME REF STATION
D18           17.699         4.260                   TIME REF STATION
D48           -0.092         0.000                   TIME REF STATION
   2011      03     22     00     00     0.0000000   TIME REF STAT DATE
                                                     END OF HEADER
```

DATA RECORD, ex: ja2rx11081.001

Epoch (reception time in the receiver time scale, ***t***)

Sampling:

0, ~~3 sec,~~
10 sec,
~~13 sec,~~
20 sec,
…



```
                                                                            END OF HEADER
> 2011 03 22 00 00 26.159947870  0  2        2.695380325 0
D01    -845050.104     -3534377.894    -57363944.03002 -57362987.80202        -130.600 7
          -123.250 7        3840.256          936.000 0         -14.900 0        51.000 0
D02    -939750.901      -185190.570    -77721725.54607 -77721623.62607        -133.050 7
          -118.350 7        3840.256         1003.398 1           3.025 1        85.326 1
> 2011 03 22 00 00 29.159947870  0  2        2.695380325 0
D01    -746274.766     -3514914.564    -57362489.77802 -57361533.49902        -130.600 7
          -123.250 7        3840.256          936.000 0         -14.900 0        51.000 0
D02    -949663.931      -187144.043    -77721871.48507 -77721769.56007        -133.050 7
          -118.350 7        3840.256         1003.398 1           3.025 1        85.326 1
> 2011 03 22 00 00 36.159947870  0  2        2.695379941 0
D01    -515085.903 0   -3469359.587 0  -57357774.07602 -57357522.36202        -130.250 7
          -125.350 7        3840.256          936.000 0         -14.900 0        51.000 0
D02    -970645.752 0    -191278.730 0  -77721528.30407 -77722078.44407        -132.700 7
          -118.000 7        3840.256         1003.398 1           3.025 1        85.326 1
> 2011 03 22 00 00 39.159947870  0  2        2.695379941 0
```


Measurements at “+3 sec.” are currently ignored in CNES processing

DATA RECORD, ex: ja2rx11081.001

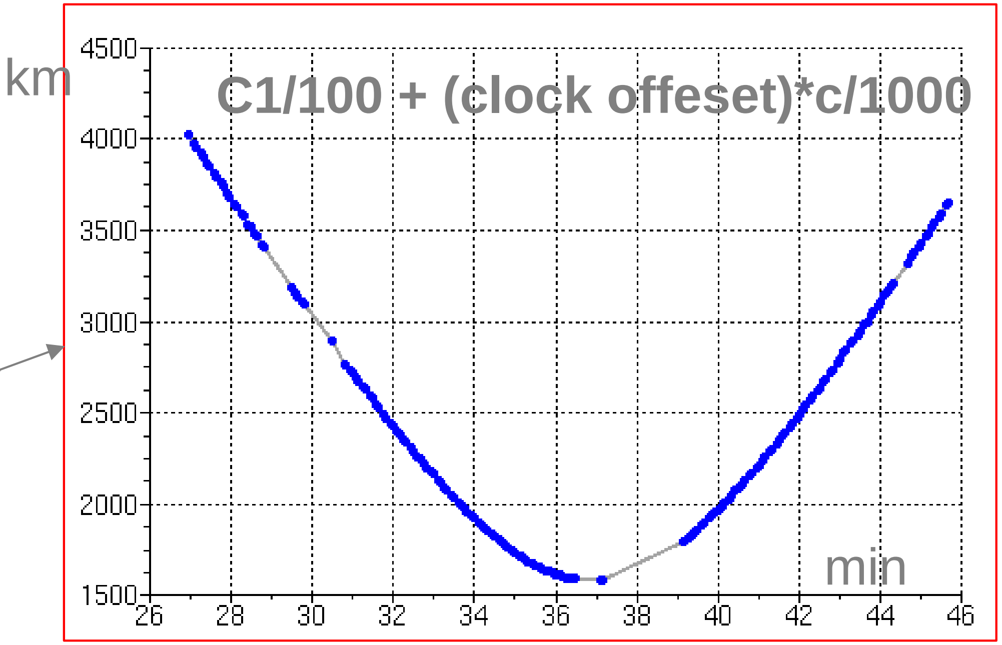
Receiver frequency offset

Receiver clock offset = ***TAI – t = -τ_r***

```
                                                                        END OF HEADER
> 2011 03 22 00 00 26.159947870  0  2        2.695380325 0
D01    -845050.104    -3534377.894   -57363944.03002 -57362907.80202       -130.600 7
          -123.250 7       3840.256          936.000 0        -14.900 0        51.000 0
D02    -939750.901     -185190.570   -77721725.54607 -77721623.62607       -133.050 7
          -118.350 7       3840.256         1003.398 1          3.025 1        85.326 1
> 2011 03 22 00 00 29.159947870  0  2        2.695380325 0
D01    -746274.766    -3514914.564   -57362489.77802 -57361533.49902       -130.600 7
```

Example on D06 time reference beacon (PAUB) :

```
> 2011 03 22 08 26 56.159947870  0  1          2.694213632 0
D05 -12332279.319 0  -2430070.839 0 -60839149.41001 -60839219.89001        -118.000 7
         -108.900 7       3840.502         1004.000 0         14.300 0         94.000 0
> 2011 03 22 08 26 59.159947870  0  2          2.694213632 0
D05 -12296500.830 0  -2423020.736 0 -60838622.63701 -60838693.10601        -118.000 7
         -108.900 7       3840.502         1004.000 0         14.300 0         94.000 0
D06     -94425.500 1    -18605.224 1 -80368121.82817 -80369271.51917        -131.300 7
         -128.500 7       3840.502         1004.000 0         23.900 0         72.000 0
> 2011 03 22 08 27  6.159947870  0  2          2.694213248 0
D05 -12208853.065 0  -2405749.869 0 -60837320.68601 -60837376.17901        -118.000 7
         -109.600 7       3840.502         1004.000 0         14.300 0         94.000 0
D06    -357816.317 1    -70506.801 1 -80373244.40207 -80372895.11407        -129.900 7
         -123.950 7       3840.502         1004.000 0         23.900 0         72.000 0
> 2011 03 22 08 27  9.159947870  0  2          2.694213248 0
D05 -12169526.395 0  -2398000.582 0 -60836741.67501 -60836797.15601        -118.000 7
         -109.600 7       3840.502         1004.000 0         14.300 0         94.000 0
D06    -470624.823 1    -92735.871 1 -80374905.24407 -80374555.97407        -129.900 7
         -123.950 7       3840.502         1004.000 0         23.900 0         72.000 0
> 2011 03 22 08 27 16.159947870  0  2          2.694212864 0
D05 -12073717.065 0  -2379121.466 0 -60835525.93201 -60835326.59701        -118.700 7
         -109.250 7       3840.502         1004.000 0         14.300 0         94.000 0
D06    -733663.431 0   -144567.965 0 -80378763.56507 -80378181.95907        -129.550 7
         -122.900 7       3840.502         1004.000 0         24.000 0         72.000 0
> 2011 03 22 08 27 19.159947870  0  2          2.694212864 0
```



Phase measurement model (noise and model errors omitted)

Beacon ref. point → Sat. CoM

2GHz phase count

Phase center correction

windup

2GHz ionospheric delay

Clock offset

$$\lambda_1 L_1 = d_0 + d_T + d_1 + \lambda_1 l_w - e + c\tau + k_1$$

$$\lambda_2 L_2 = d_0 + d_T + d_2 + \lambda_2 l_w - \gamma e + c\tau + k_2$$

Ambiguities

400MHz phase count

Tropospheric delay

Square of frequency ratio (~25)

Phase measurement model

See also backup slide “Frequency shifted beacons” for more details

phase count *L*: phase is counted on the – (received – nominal) beat frequency; on board nominal frequencies are always 2036.25 MHz and 401.25 MHz

$$\lambda_1 L_1 = d_0 + d_T + d_1 + \lambda_1 l_w - e + c\tau + k_1$$

$$\lambda_2 L_2 = d_0 + d_T + d_2 + \lambda_2 l_w - \gamma e + c\tau + k_2$$

Ground nominal frequencies are generally the same as on-board nominal frequencies, except for frequency shifted beacons (k-factor<>0)

c/λ_1=543*5e6*(3/4 + 87*K/(5*2^26)) and c/λ_2=107*5e6*(3/4 + 87*K/(5*2^26))

Phase measurement model

Phase windup is currently not modeled

(partly accommodated by estimating a bias per pass for LEO satellites)

$$\lambda_1 L_1 = d_0 + d_T + d_1 + \cancel{\lambda_1 l_w} - e + c\tau + k_1$$

$$\lambda_2 L_2 = d_0 + d_T + d_2 + \cancel{\lambda_2 l_w} - \gamma e + c\tau + k_2$$

Iono-free phase measurement model

$$\lambda_c L_c = d_c + c\tau + a$$

$$\lambda_C L_C \equiv \frac{\gamma\lambda_1 L_1 - \lambda_2 L_2}{\gamma - 1}$$

iono-free combination of the phase measurements

Iono-free phase measurement model

$$\lambda_c L_c = d_c + c\tau + a$$

Propagation distance between iono-free phase centers

$$d_c \equiv d_0 + \frac{\gamma d_1 - d_2}{\gamma - 1} + h_{dry} + m_{wet} h_{z,wet}$$

tropospheric delay d_T

Iono-free phase measurement model

$$\lambda_c L_c = d_c + c\tau + a$$

$$a \equiv \frac{\gamma k_1 - k_2}{\gamma - 1}$$

Ambiguity:

bias per each set of continuous phase measurements

eliminated by differentiating measurements at successive epochs (classical Doppler-like processing) within the same set

Iono-free phase measurement model

$$\lambda_c L_c = d_c + c\tau + a$$

$$c\tau \equiv c(\tau_r - \tau_e)$$

Clock offset:

polynomial clock models are currently used to model the receiver τ_r and emitter τ_e clock offsets

The independent variable used for clock models is the on-board time (hereafter designated with *t*).

Relationship between on-board time *t* and TAI (*T*) is given by $\boldsymbol{t = T + \tau_r}$

(see pseudorange definition in the RINEX format document)

Clock models

- **Emitter (beacon) clock model:**

$$\tau_e = a_0 + a_1 t + \delta a_0 + \delta a_1 t$$

A-priori clock-offset model is either 0 or the value given by the linear model in the TIME_REF_STATION section of the rinex header

Clock models

- **Emitter (beacon) clock model:**

$$\tau_e = a_0 + a_1 t + \delta a_0 + \delta a_1 t$$

In general, a linear clock model per pass should be estimated for all beacons.

In the case of doppler-like processing, the δa_0 term is eliminated by differentiating measurements at successive epochs within the same pass. The δa_1 coefficient is equivalent to the usual frequency bias per pass

Clock models

- **Receiver clock model:**
  - **Available in the RINEX file's data records ($-\tau_r$)**
  - **…or computed using the pseudo-range measurements:**

    in this latter case, the clock model is a deg. 2 or 3 polynomial (depending on the arc length), whose coefficients are estimated

  (see slide on pseudo-range measurement model**)**

$$\tau_r = \sum_{i=0}^{N} b_i t^i$$

Pseudo-range measurement model (noise and model errors omitted)

$$C = d + c(\tau_r - \tau_e)$$

$$\tau_r = \sum_{i=0}^{N} b_i t^i$$

- Given the level of noise (~1km), it is not important whether C is the iono-free combination or not
- *d* is the propagation distance, it can be computed with an orbit having ~ 100 m accuracy (for < 1 microsec. accuracy)
  - An extrapolated orbit over 2 days is usually sufficient (MOE-like processing)
- Our datation processing
  - measurements from time ref. beacons only
  - MOE: 2-day batch, solve for b0,b1,b2, all time ref. beacons held fixed
  - POE: 10-day batch, solve for b0,…,b3, solve for a bias per time ref. beacon (TLSB fixed)

Processing equation summary for the Doppler case

$$\lambda_c \Delta L_c = \Delta d_c + \Delta m_{wet} h_{z,wet} + c\Delta\tau_r + \Delta t \cdot c\delta a_1$$

+ errors and noise

- Δ represents the operator that differentiate two successive measurements within the same pass
- The zenith wet troposheric delay and the beacon clock drift are estimated per pass
- The receiver clock is assumed to be known (from polynomial model or from Rinex data record) – errors in this model will be partly accommodated by δa_1

Processing equation of the DORIS observable in 2.2 format

- 2.2 format: every quantity refers to the 2GHz frequency
- The only time-scale is TAI, hereafter indicated with *T*
- The observable is an average range rate *V*, computed over the count interval ΔT*, defined as*

$$V \equiv \frac{c}{f_1}\left(f_1 - \langle f_{sat} \rangle - \frac{D}{\Delta T} \right)$$

2GHz cycle count

Nominal beacon frequency (including k-factor shift)

Count interval (TAI)

Best estimate of the actual satellite frequency (includes long term drift of the clock wrt to TAI)

(Definition given in ftp://ftp.ids-doris.org/pub/ids/data/doris22.fmt)

RINEX L1 observable → 2.2 format radial rate observable

$$D = -\Delta L_1$$

In the RINEX file, the sign of the phase count *L* is changed to be consistent with the pseudo-range

$$\Delta T = \Delta t - \Delta \tau_r$$

Relationship between TAI (*T*), on-board time (*t*), and clock error (τ)

$$\left.\begin{aligned} \Delta\phi &\equiv \int_{T_0}^{T_0+\Delta T} f_{sat}(T)\,dT \\ \langle f_{sat} \rangle &\equiv \frac{\Delta\phi}{\Delta T} \\ \Delta t &\equiv \frac{\Delta\phi}{f_{sat,0}} \end{aligned}\right\} \Rightarrow \langle f_{sat} \rangle = f_{sat,0}\frac{\Delta t}{\Delta T}$$

$\langle f_{sat} \rangle$ is the mean frequency over the count interval

This is how we compute the radial rate observable in 2.2 files

$$V \equiv \frac{c}{f_1}\left(f_1 - \langle f_{sat} \rangle - \frac{D}{\Delta T} \right)$$

2.2 format radial rate observable → RINEX L1 observable

$$V = \frac{\Delta d_0 - c\Delta\tau_e}{\Delta T}$$

In the 2.2 file , the radial rate observable is the relative velocity between the beacon reference point and the satellite CoM, uncorrected for the beacon frequency bias

$$\frac{c}{f_1}\left(f_1 - \langle f_{sat} \rangle - \frac{D}{\Delta T} \right) \cdot \Delta T = \Delta d_0 - c\Delta\tau_e$$

Using the same expression as in the previous slides …

$$-c\Delta\tau_r + \lambda_1 L_1 = \Delta d_0 - c\Delta\tau_e$$

$$\lambda_1 \Delta L_1 = \Delta d_0 + c(\Delta\tau_r - \Delta\tau_e) + corrections...$$

Data corrections in 2.2 format

- Ionospheric delay rate

$$\frac{\Delta e}{\Delta T} = \frac{1}{\Delta T}\left(\frac{\lambda_1 \Delta L_1 - \lambda_2 \Delta L_2}{(\gamma - 1)} - \frac{\Delta d_1 - \Delta d_2}{(\gamma - 1)}\right)$$

- Phase center correction rate

$$-\frac{\Delta d_1}{\Delta T}$$

2.2 format: "All corrections (ionosphere, troposphere, and center of mass) should be added to observed values or subtracted from computed values"

- Tropospheric delay rate

$$\frac{\Delta d_T}{\Delta T} = -\frac{\Delta h_{dry} + \Delta m_{wet} h_{z,wet}}{\Delta T}$$

- The above corrections are computed with a preliminary orbit determination process

Conclusion

- We encourage users to move towards the “new” RINEX format
- RINEX allows each analysis center to be independent from CNES data preprocessing, as users have access synchronous dual frequency phase and pseudorange measurements
- 3 years of data (from Jason-2 launch) exist in both formats (2.2 and RINEX) → allows validation
- Measurement model is more clearly formulated
- 2.2 data production should stop at some point in time (HY2A?)

backups

Frequency shifted beacons (k-factor)

- L: counted on the – (received – nominal) beat frequency $L = -(\varphi_r - \varphi_0) + k$
- Relationship between phase and receiver time $t \equiv \dfrac{\varphi_0}{f_0} + const., t = T + \tau_r$
- On board nominal frequency : k=0 (always 2036.25 MHz and 401.25 MHz)
  Received phase = phase at emission time (subscript *e* denotes emitter)

$$L = -f_k(T_e + \tau_e) + f_0(T + \tau_r) = f_k(T - T_e) + f_k(\tau_r - \tau_e) + c\left(\frac{f_0 - f_k}{f_k}\right)t$$

L is the phase count on either one of the 2 frequencies; ambiguities omitted

$$\frac{c}{f_k} L = d + c\tau + c\frac{f_0 - f_k}{f_k} t$$

→ *This term has been omitted in the phase measurement model. It is = 0 except for frequency shifted beacons (today GAVB,GR3B). If omitted, it is accommodated by the estimated beacon clock drift per pass*

In the equation above ***d*** is the full propagation path;
including all corrections (tropo, iono, phase center, windup)