Mark-Jan PE1CMP

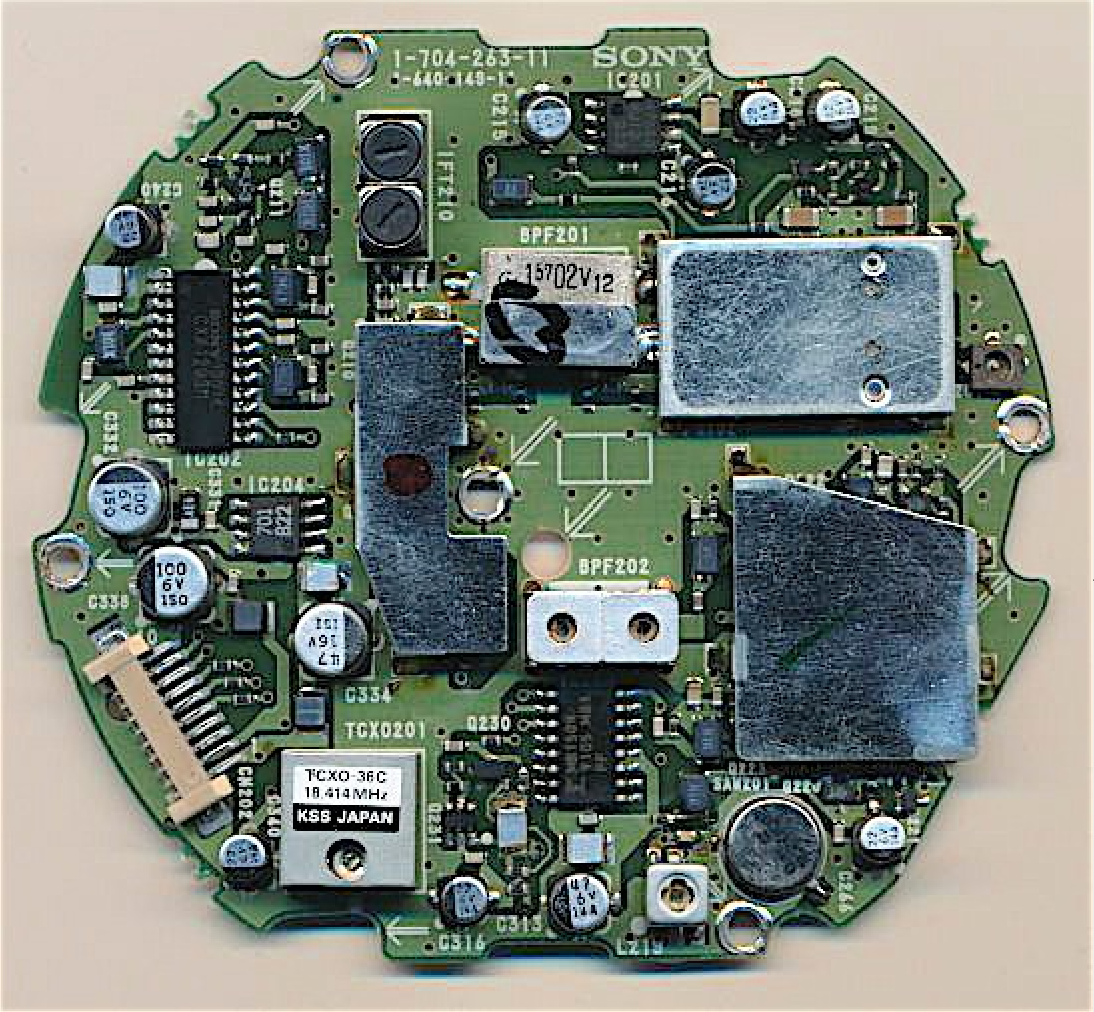
12 Juli 2020

Tijd-ontvangst met open-source en zelfbouw GPS ontvangers

- GPS is een publiek/gepubliceerd signaal

Bron: https://www.rand.org/content/dam/rand/pubs/monograph_reports/MR614/MR614.pdf
Bron: https://www.gps.gov/technical/icwg/IS-GPS-800F.pdf

- Eerste civiele GPS ontvanger
- Sony Pyxis IPS-360 (1991)

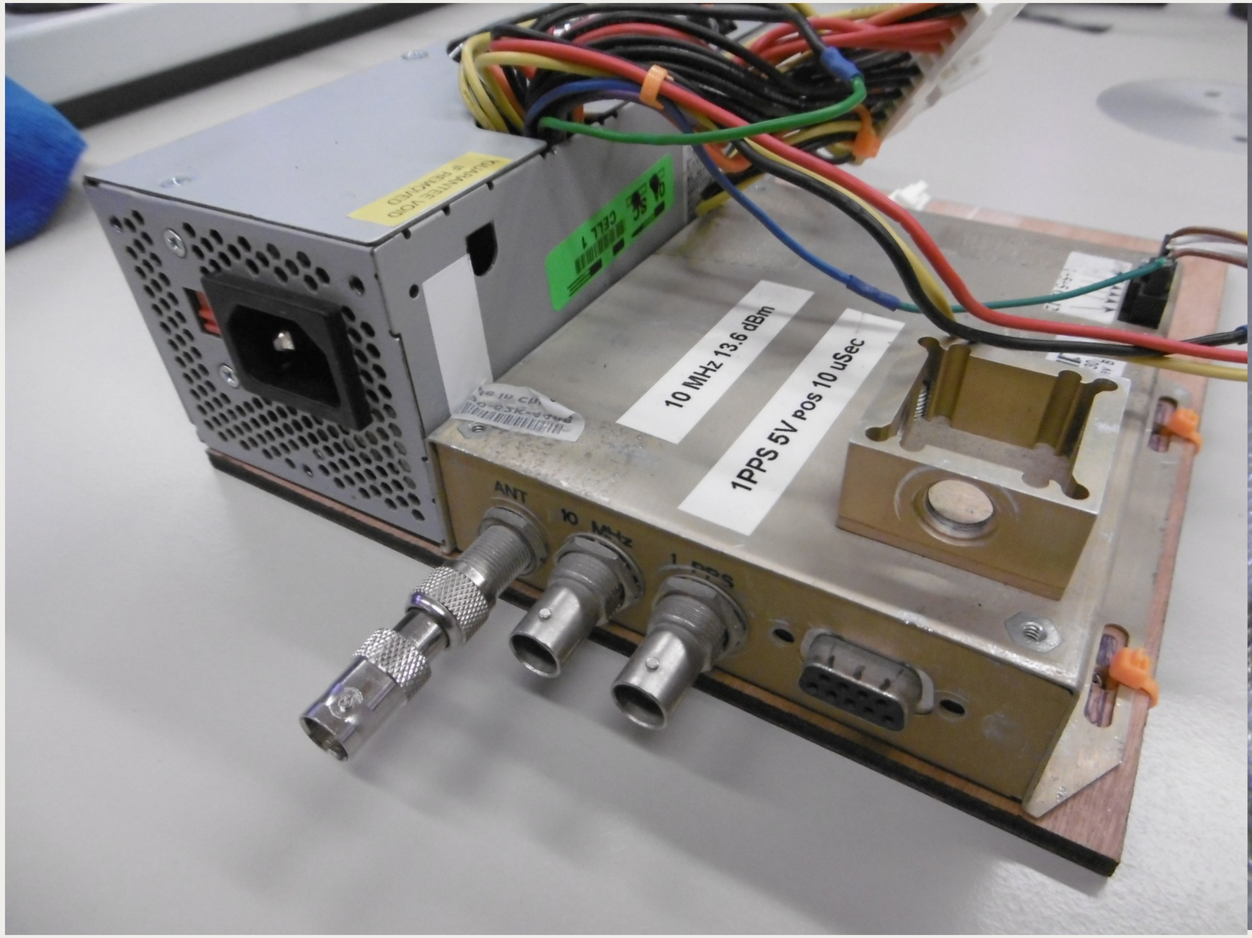


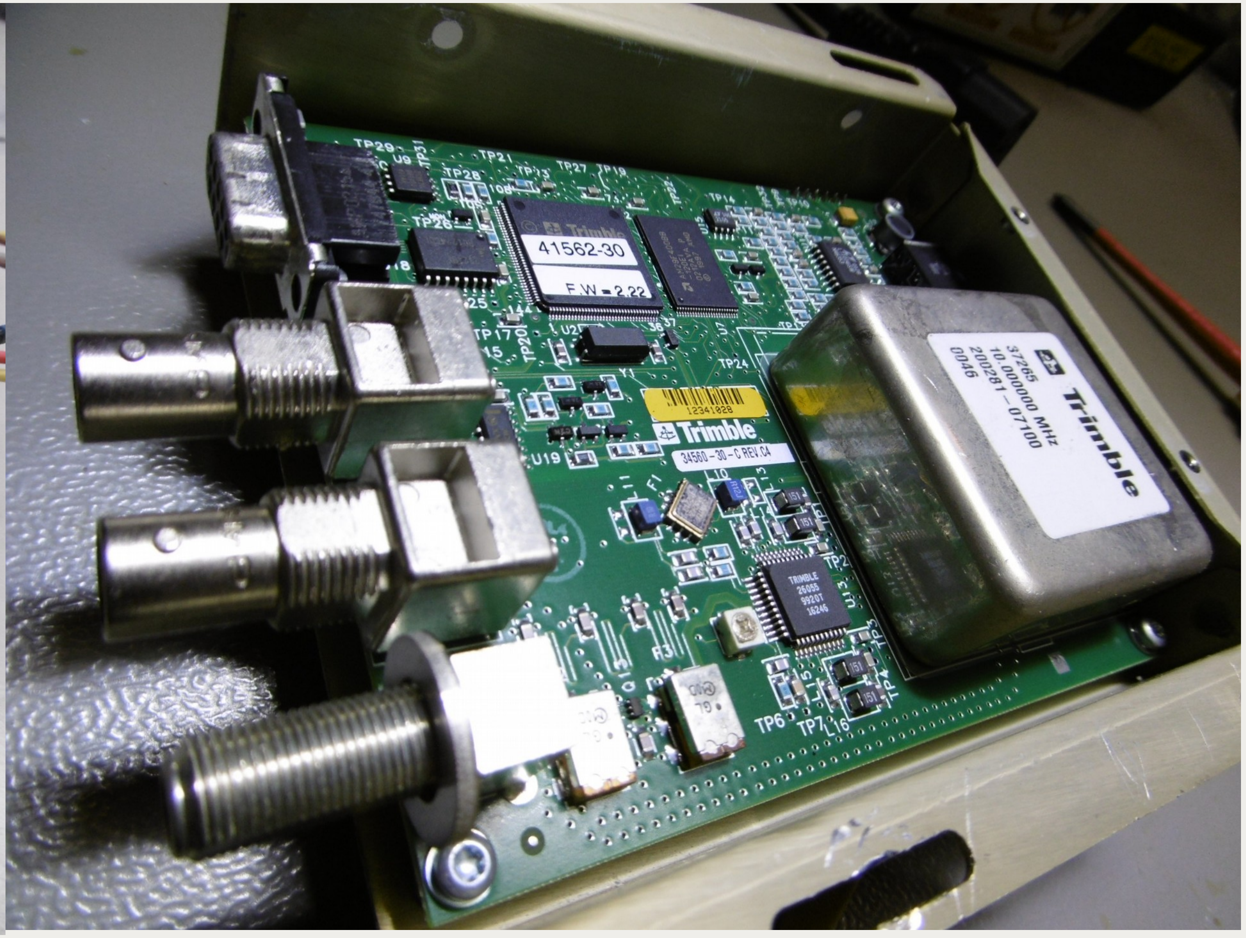
Bron: http://retro-gps.info/Sony/Sony-Pyxis-IPS-360/index.html

- GPS tijd

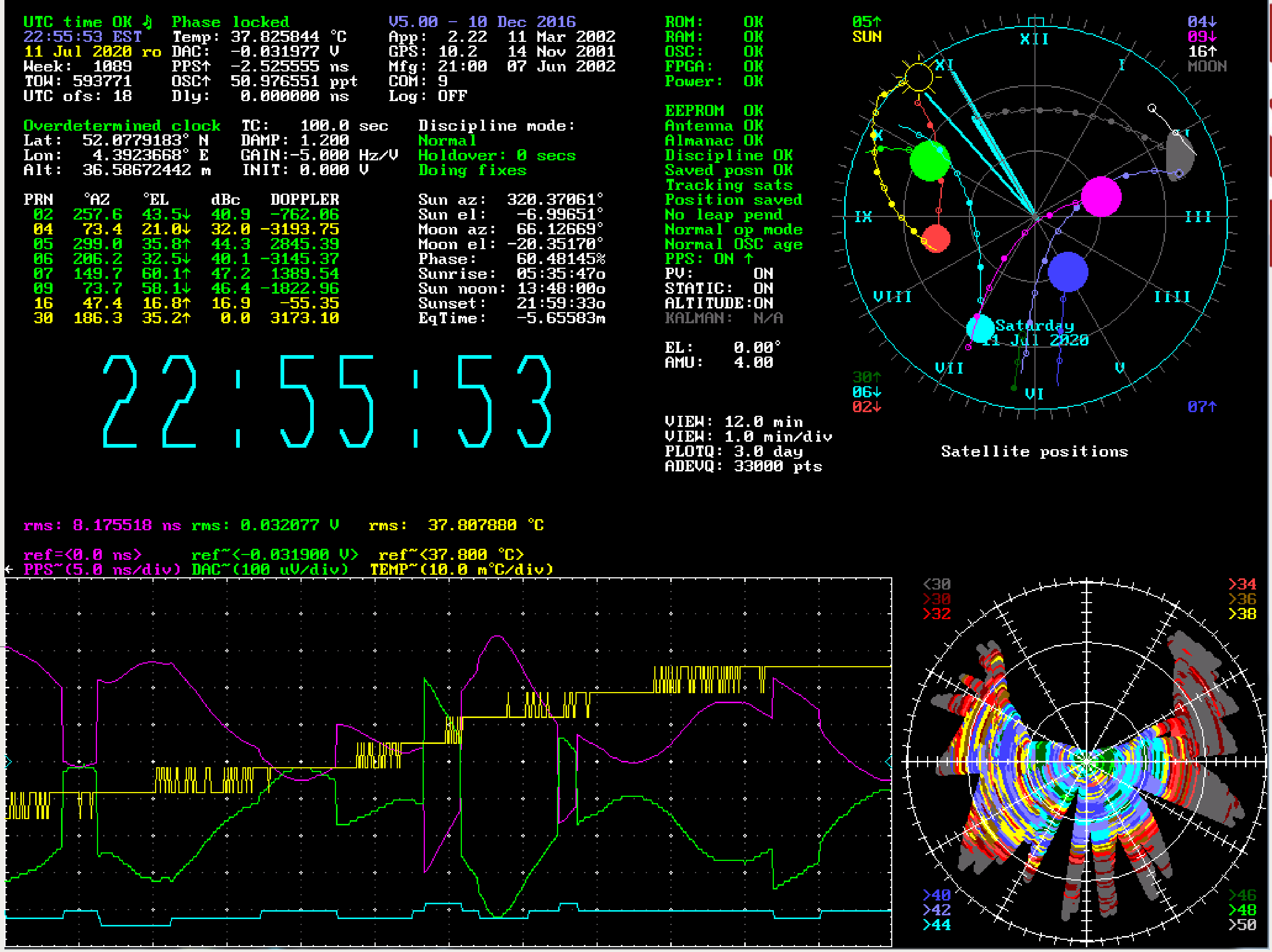
  Eenvoudigste oplossing: doosje met stekkers

- GPSDO
- Trimble Thunderbolt (uit oude GSM basestation)
- Eenvoudig in gebruik: +12 / -12 / +5V
- Serial output in TSIP, bijv naar Windows (DOS) programma ‘Lady Heather’





- Lady Heather



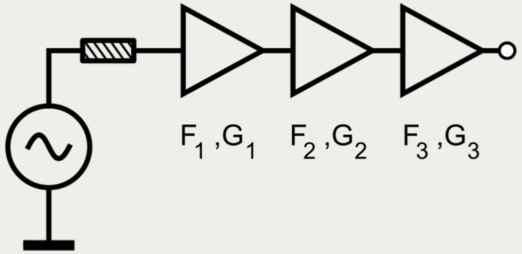
http://www.ke5fx.com/heather/readme.htm

http://www.ke5fx.com/heather/readme.htm

Lady Heather supported hardware

- Trimble Thunderbolt and Thunderbolt-E
- Acron Zeit WWVB receiver
- UCCM - Trimble / Symmetricom GPSDOs
- DATUM STARLOC II GPSDO
- NEC GPSDO (STAR-4 compatible)
- GPSD interface
- Jupiter-T (aka Zodiac)
- Lucent KS24361 REF0/Z3811A (19200:8:N:1)
- Motorola binary format
- Generic NMEA receiver
- Trimble Resolution T family with odd parity
- Sirf binary
- Generic Trimble TSIP binary
- Ublox UBX binary
- Venus mixed binary / NMEA
- Nortel SCPI-compatible GPSDOs (NTWB, NTPX, etc.)
- Z3801A and compatible SCPI GPSDOs
- HP 5xxxx-style SCPI
- Oscilloquartz STAR-4 (via the management interface)
- NVS binary
- PC system clock (no receiver)

Keuze van antenne voor GPSDO



- Ruisgetal van eerste versterker is dominant
  (Friis formula for noise)

$$F_{\text{total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}}$$

- Dit is de versterker
  - in de antenne
  - of op de module met eigen ceramic patch-antenna

- Lengte kabel tussen het phase-center van de GPS antenne en digitalisatie-stap in ontvanger wordt onderdeel van de ‘common pseudo-range bias’

- Abusievelijke capacitieve koppeling in GPS-DO kabel / clockdistributie connector heeft tot een constatering van ‘neutrino’s sneller dan het licht’ geleid...

- Antenna: Aliexpress...

Bands	GPS L1 L2	GLONASS G1 G2	GALILEO E1 E5b
Gain at Zenith	L1≥5.5dBi L2≥5.0dBi	G1≥5.0dBi G2≥5.0dBi	E1≥5.0dBi E5b≥4.5dBi
Polarization	RHCP		
Horizontal Coverage	360^o		
Output Impedance	50Ω		
Output VSWR	≤1.5		
Axial Ratio at Zenith	≤3dB		
Phase Center Accuracy	≤2mm		

https://beitian.en.made-in-china.com/product/gCUnrKpPHyhD/China-Beitian-Gnss-Antenna-3V-18V-Zed-F9p-High-Gain-Cors-Rtk-Glonass-Beidou-Galileo-GPS-Antenna-High-Precision-Survey-Gnss-Antenna-TNC-K-Bt-290.html

- Low-noise Amplifier integrated with antenna

Low Noise Amplifier	
Gain	(40±2)dB
Noise Figure	≤1.8dB
Input VSWR	≤2.0
Output VSWR	≤2.0
Delay of Differential Transmission	≤5ns
Supply Voltage	3.0V - 18.0V
Supply Current	≤45mA
Mechanical Characteristics	
Dimensions	Φ150mm*63.7mm
Connector	TNC-K
Weight	400g
Ingress Protection	IP67

- Bronnen van interferentie / blocking
- L-band

1,558.450	33278	INMARSAT 4-F3	97.57W	3372bps QPSK - Inmarsat AMSC LES rep. pat/idle
1,575.420	24307	INMARSAT 3-F2	178.55E	EGNOS overlay
1,575.420	39215	ALPHASAT (I-4A F4)	24.51E	Egnos overlay data (xBr recording)

Bron: https://uhf-satcom.com/satellite-reception/l-band

GPS en GNSS theorie

GNSS – Global Navigation Satellite System(s)

- Frequenties
- Signalen op die frequenties – **allemaal pseudo-random ‘noise’**

- Methodes van ontvangst van de signalen (correlatie/de-spreading, demodulatie)

- Werken met known-data (A-GPS databit wipe-off/gevoeligheidsverbetering)

- Verwerking van de data tot een volledig bericht
  (GPS: 30 seconden per satelliet, of 12.5 minuten voor complete ‘almanac’-download incl UTC offset)

- Verwerking van de pseudo-ranges tot een PVT (position-velocity-tijd) oplossing

- Ontvangen tijdinformatie inzetten voor sturing van de OCXO

- Bronvermelding: 2007
- Aalborg University
- http://gps.aau.dk/softgps ← onbereikbaar
  In spring 2012 the scientific management for
  Aalborg University decided to discontinue
  the master study in GPS Technology at Aalborg University.
- http://ccar.colorado.edu/gnss

- Birkhauser
- ISBN-13 978-0-8176-4390-4
- ISBN-10: 0-8176-4390-7
- DVD ?

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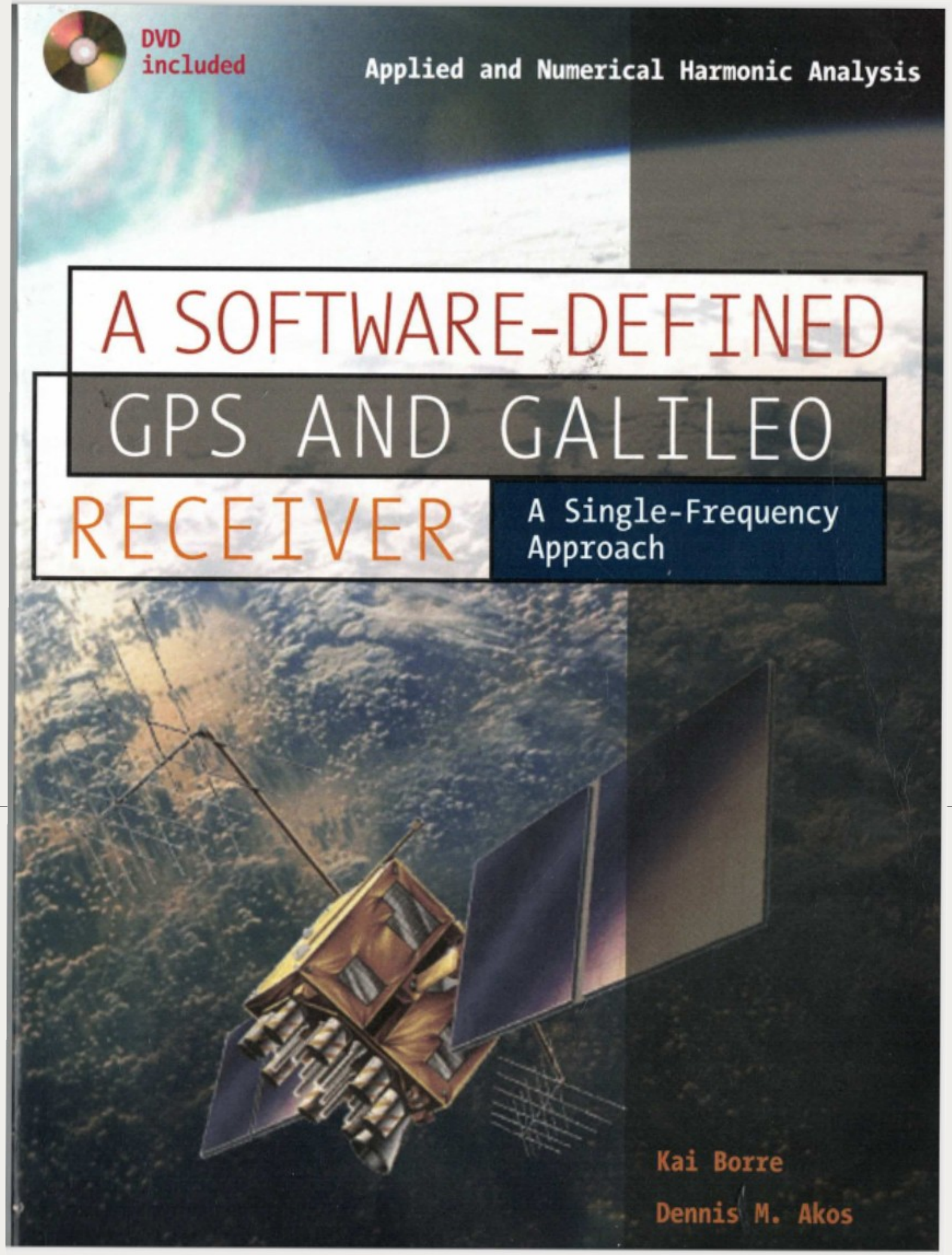
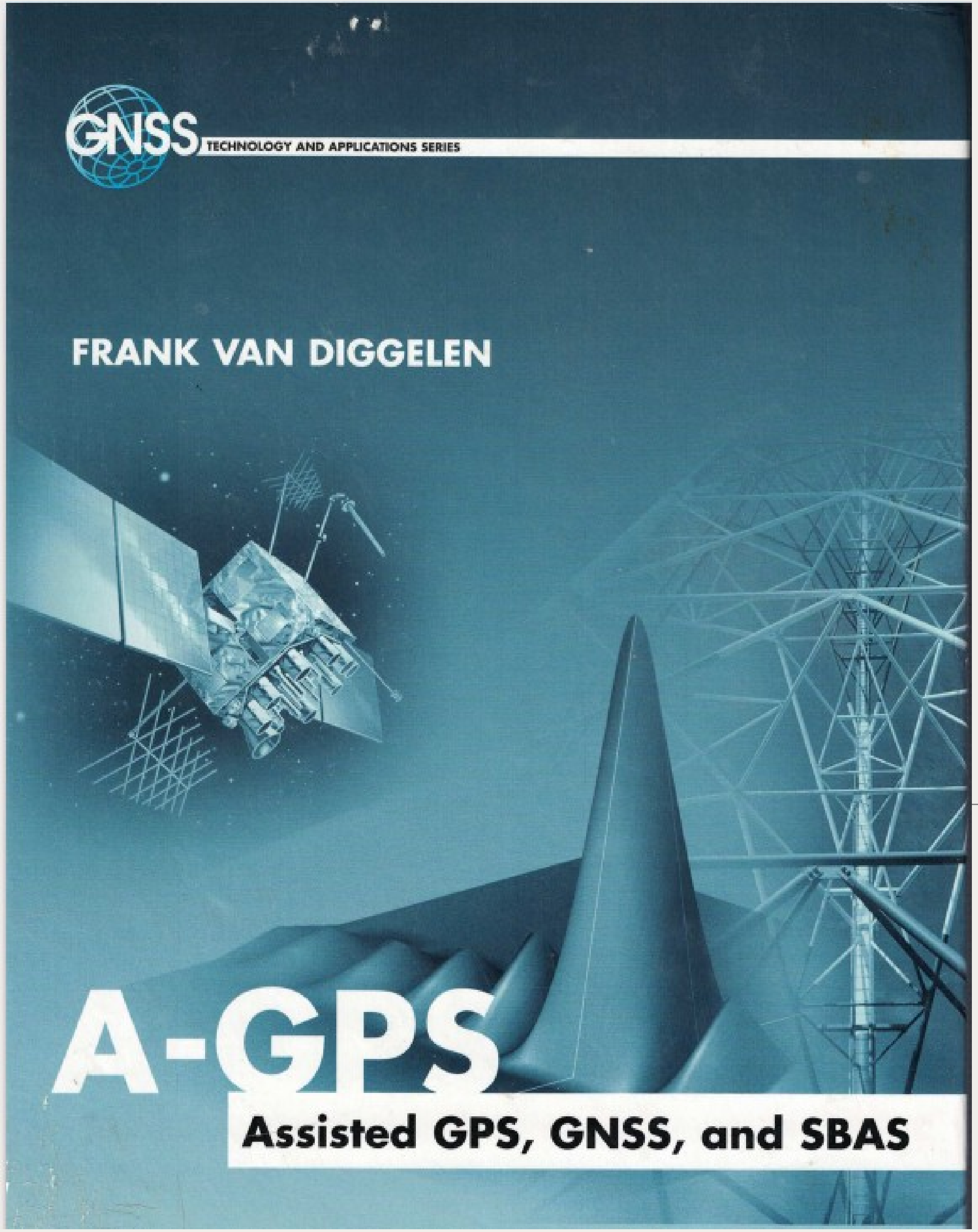
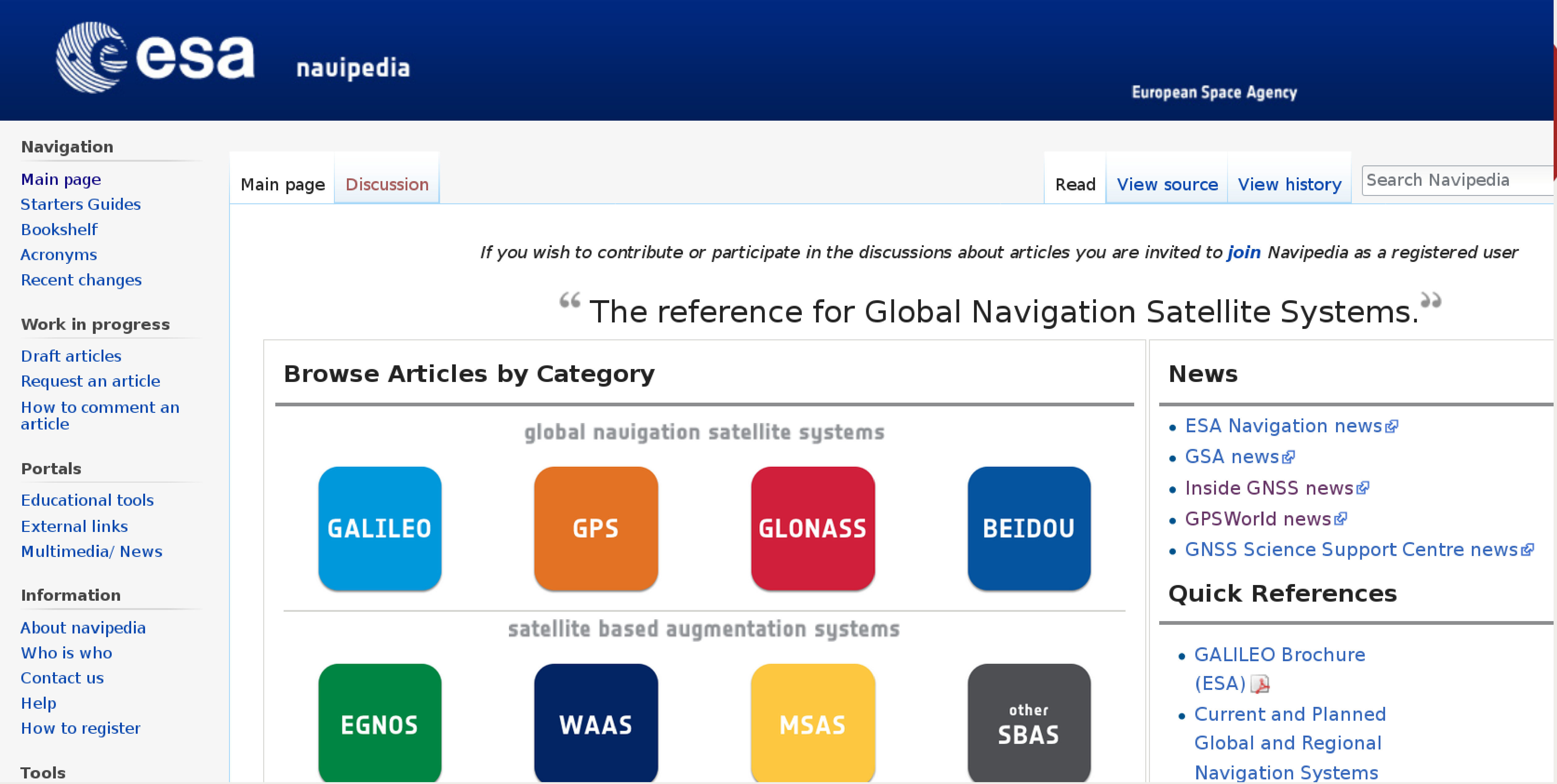
Soren Holdt Jensen



A-GPS Assisted GPS, GNSS and SBAS
Frank van Diggelen
2009

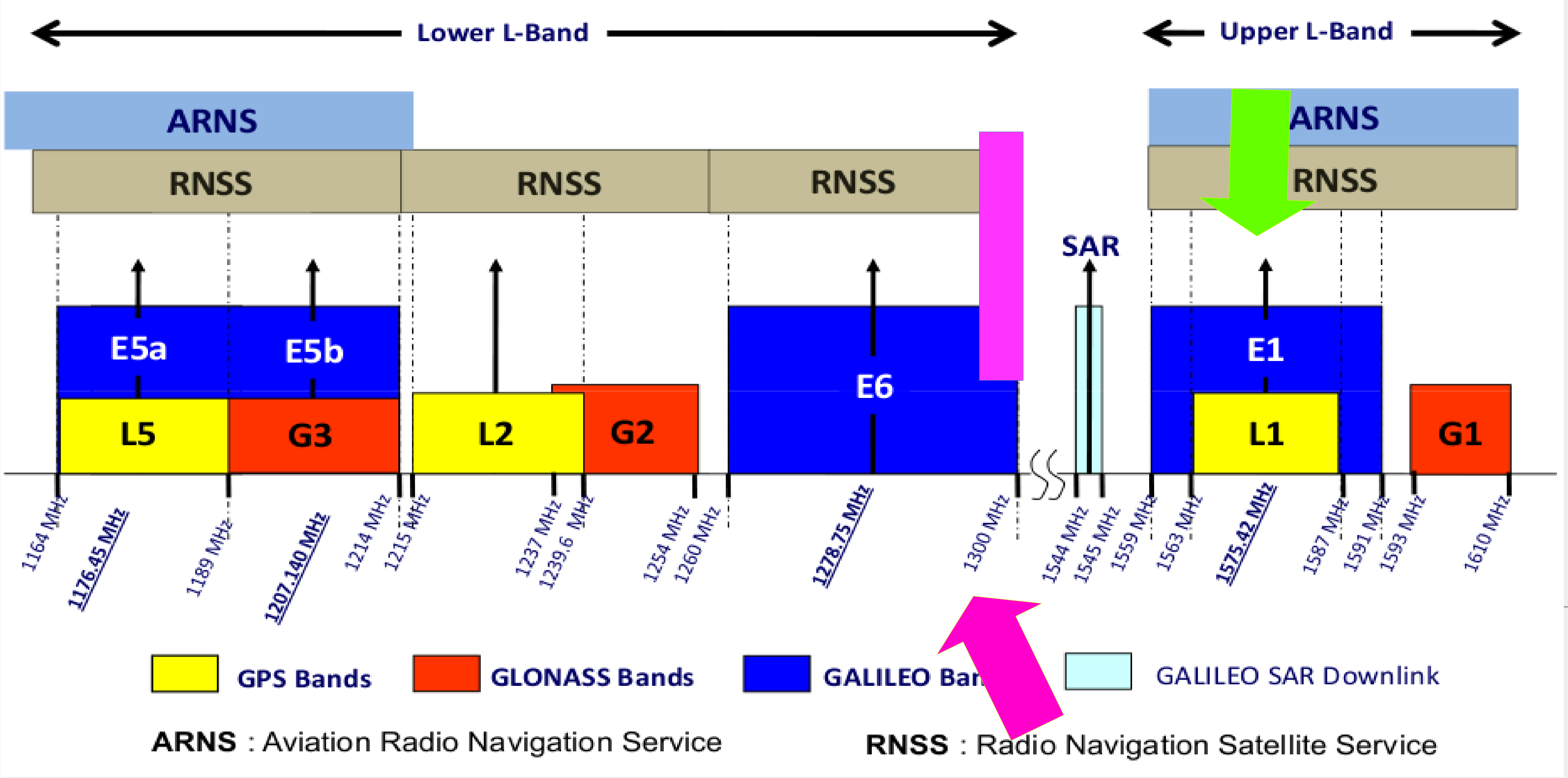
ISBN-13: 978-1-59693-374-3
ISBN-10: 1-59693-374-7





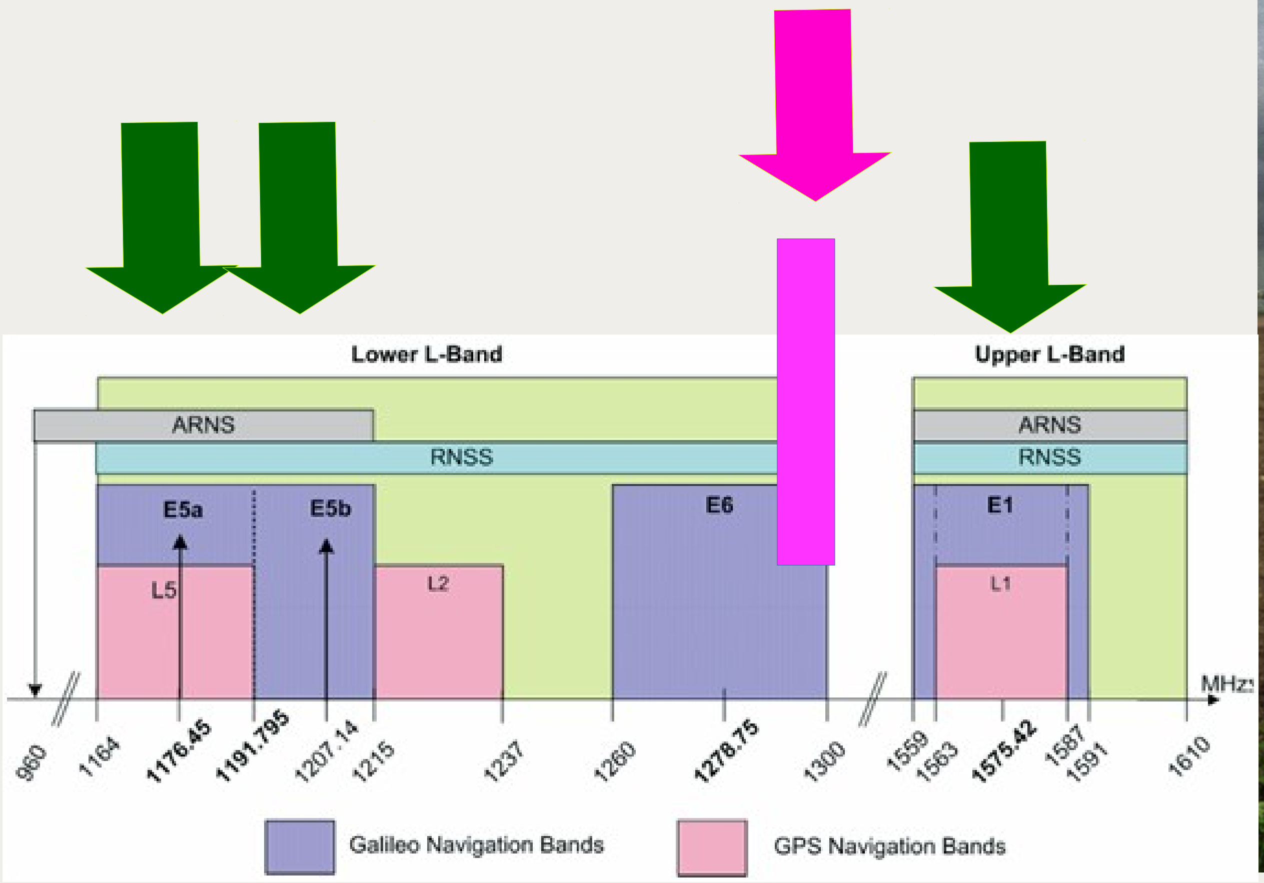
Bron: https://gssc.esa.int/navipedia/index.php/Main_Page

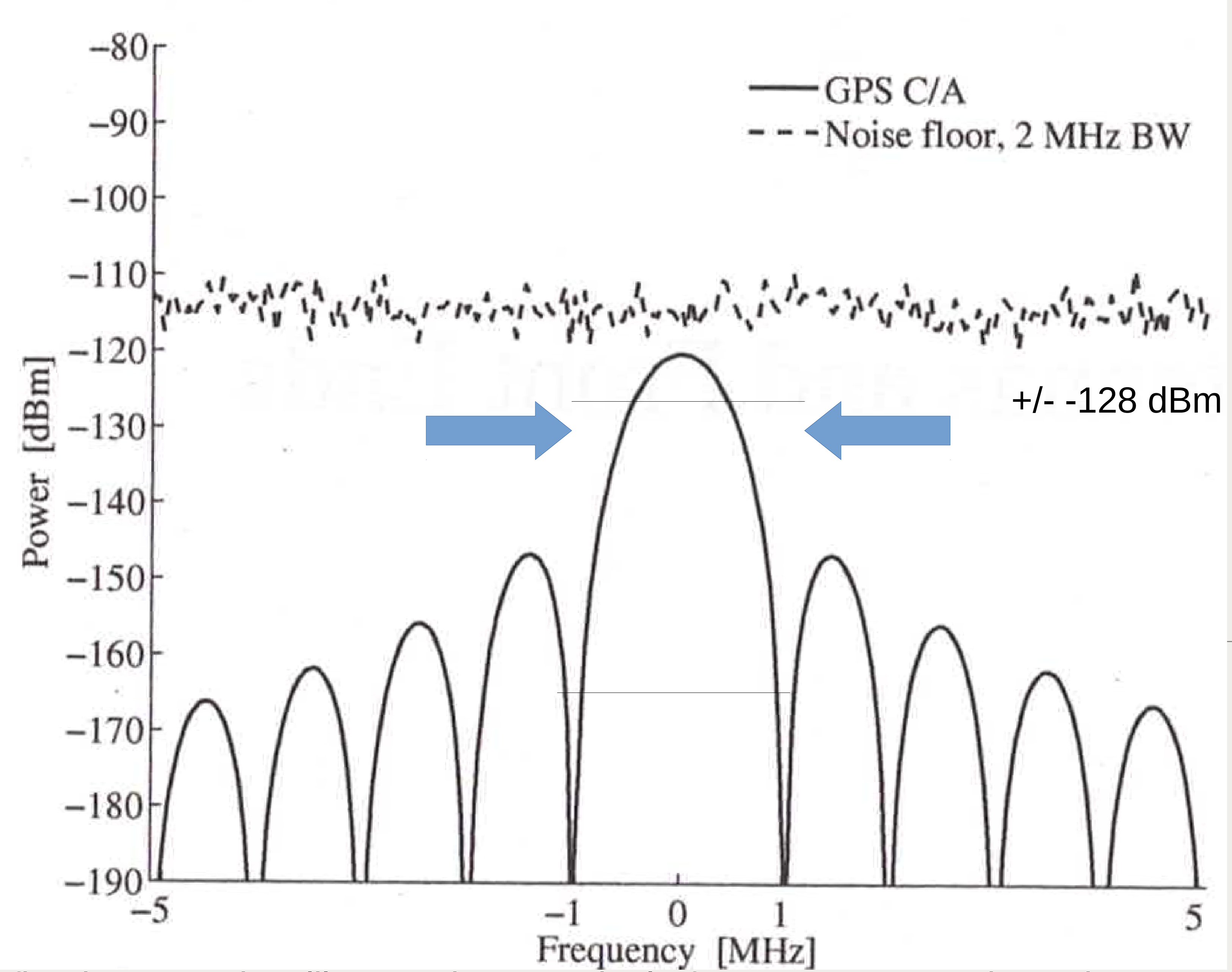
GNSS overzicht



Bron: https://gssc.esa.int/navipedia/index.php/GNSS_signal
Bron: https://gssc.esa.int/navipedia/index.php/Main_Page
Bron: A-GPS Assisted GPS, GNSS and SBAS – Frank van Diggelen

- E6 1273.75-1283.75
- https://gssc.esa.int/navipedia/index.php/Galileo_High_Accuracy_Service_(HAS)





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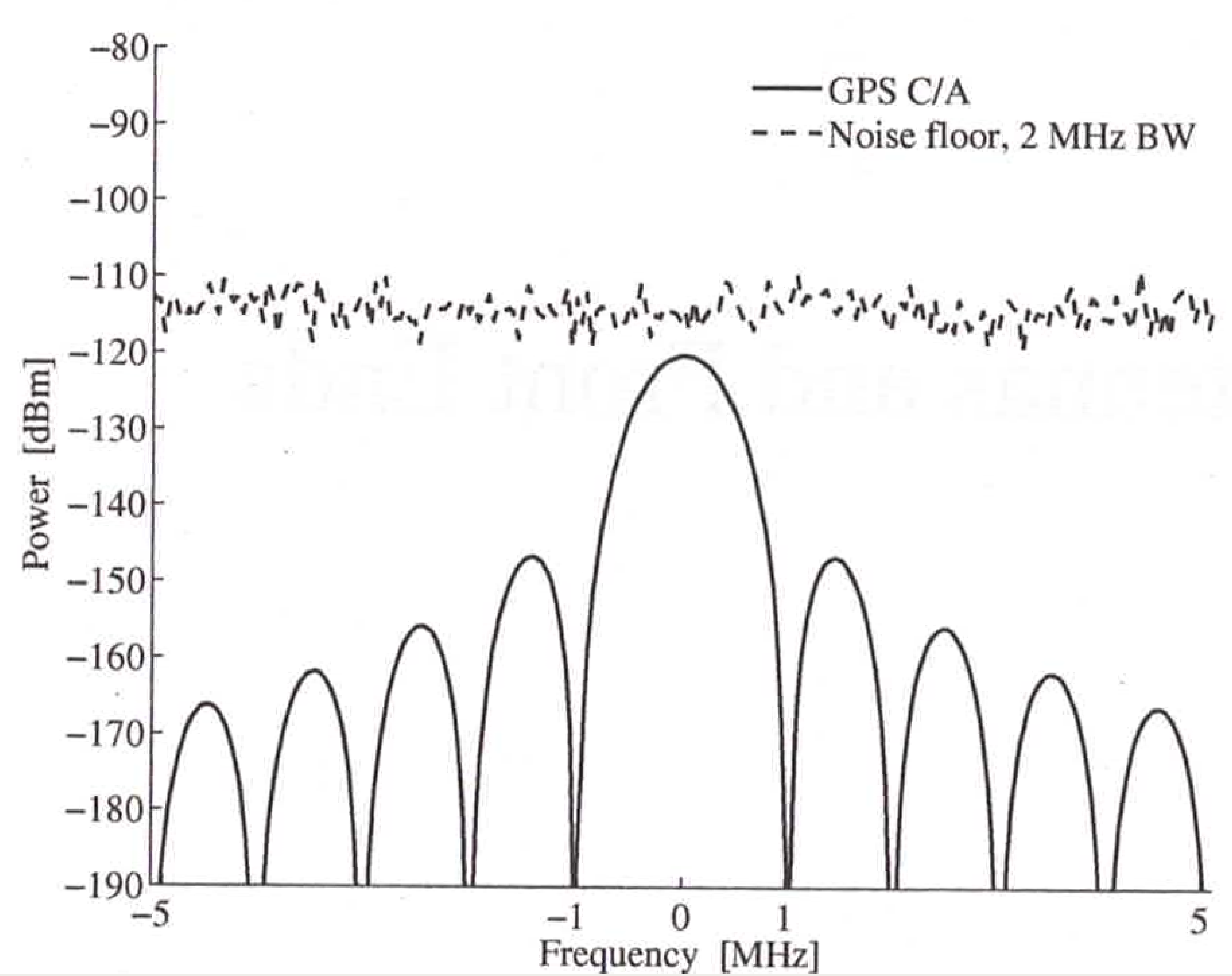
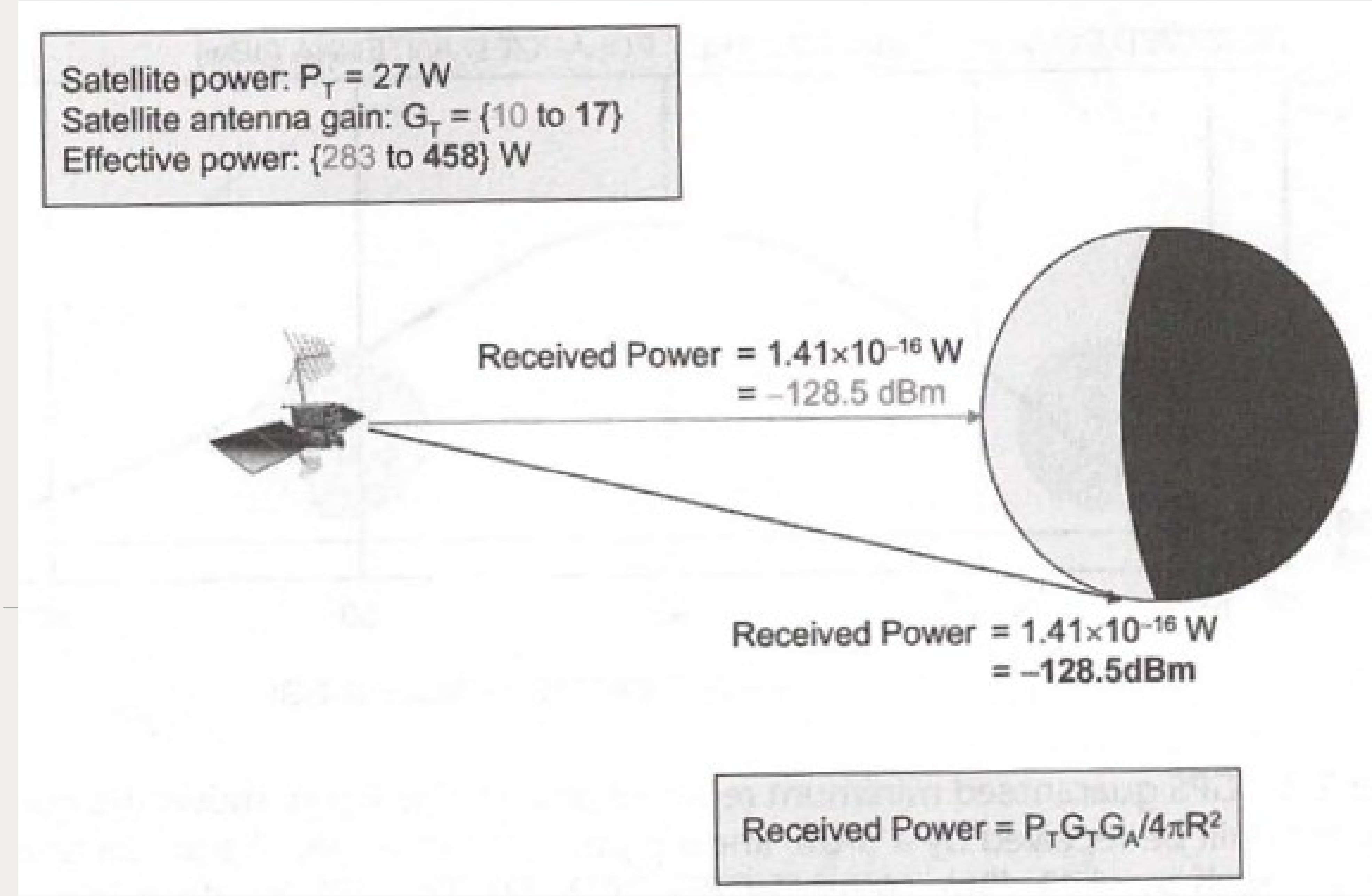
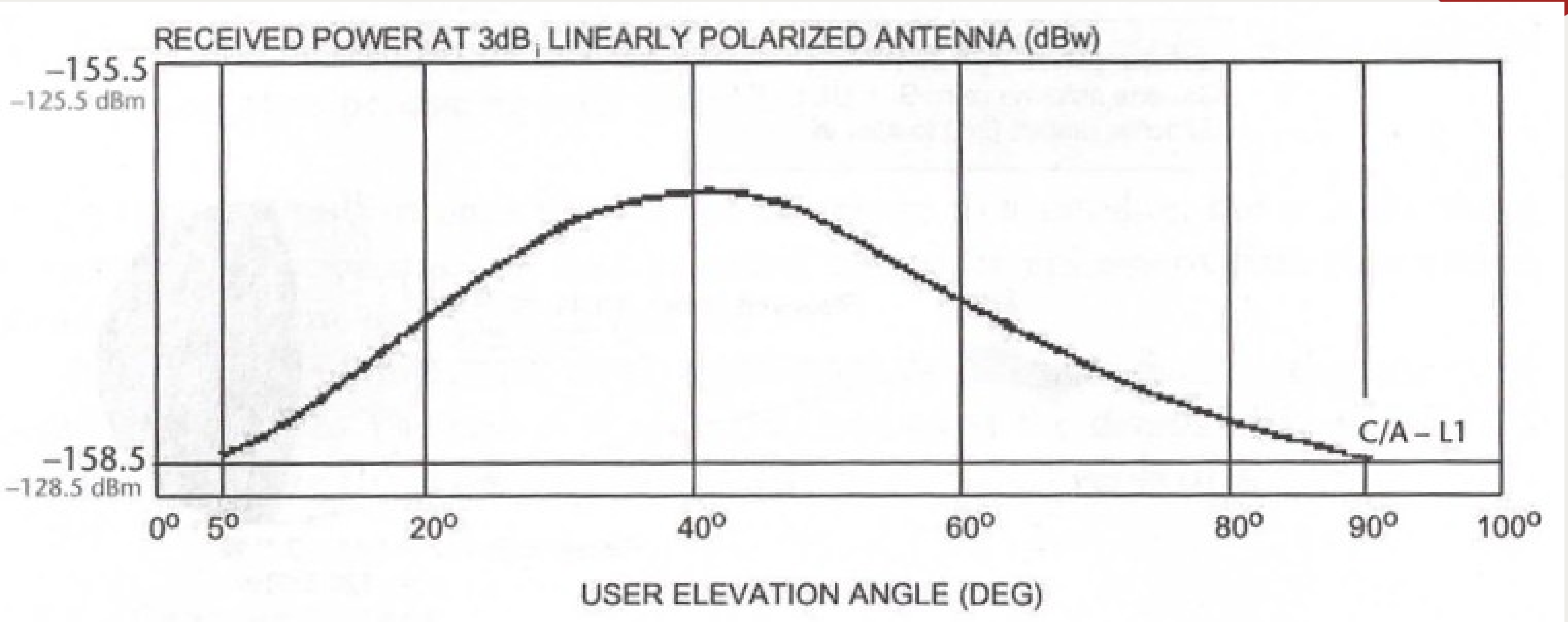
- Galileo


GPS C/A
Noise floor, 2 MHz BW
Power [dBm]
−80
−90
−100
−110
−120
−130
−140
−150
−160
−170
−180
−190
−5
−1
0
1
5
Frequency [MHz]



Bron: A-GPS Assisted GPS, GNSS and SBAS – Frank van Diggelen

Power afhankelijk van elevation (hoek van inval op antenne)
- 27 watt gericht op de aarde
- 100 attowatt buiten, binnen 0 tot 10 attowatt
- Acquisitie GPS data (1e 30 seconden) heeft 50 bps betrouwbaarheid nodig
  - integratietijd < 20 msec (50 bps data)



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Carrier – CW signaal 1575.42 MHz
- Real continuous (niet onderbroken!) wave

1540 carrier-cycles voor elke ‘chip’
  - ca 1 usec (1/1023) msec

1023 chips = 1 PRN sequence

20 PRN sequences = 1 bit (50 bps)

Correlatie als ontvangstmethode
- In tijddomein

RF Seminar

1x PRN sequence ‘A’ = 1023 chips = 1 msec

1 … 20 of zelfs 40 msec met data-wipeoff

PRN lock over 1...20 msec

0 0 1 1 1 0 0 1 0

20x PRN sequence ‘A’ = 20x1023 ‘chips’ = 20 msec

50 bps - ‘0’ --->

0 0 1 1 1 0 0 1 0 | 0 0 1 1 1 0 0 1 0 | ... | 0 0 1 1 1 0 0 1 0

20x PRN sequence ‘A’ = 20x1023 ‘chips’ = 20 msec

50 bps - ‘1’ --->

1 1 0 0 0 1 1 0 1 | 1 1 0 0 0 1 1 0 1 | ... | 1 1 0 0 0 1 1 0 1

Digitaliseren van ruis: Integreren van kansen op 1 en 0 ‘chip’, optellen, en over 1 tot 20 milliseconden checken of correlatie Positief (bit==1) of Negatief (bit==0) is

- Alternatief: software in frequentiedomein (via FFT/ iFFT over signaal van die lengte)

Auto-correlatie (ACF) properties GPS C/A ‘Gold’ codes

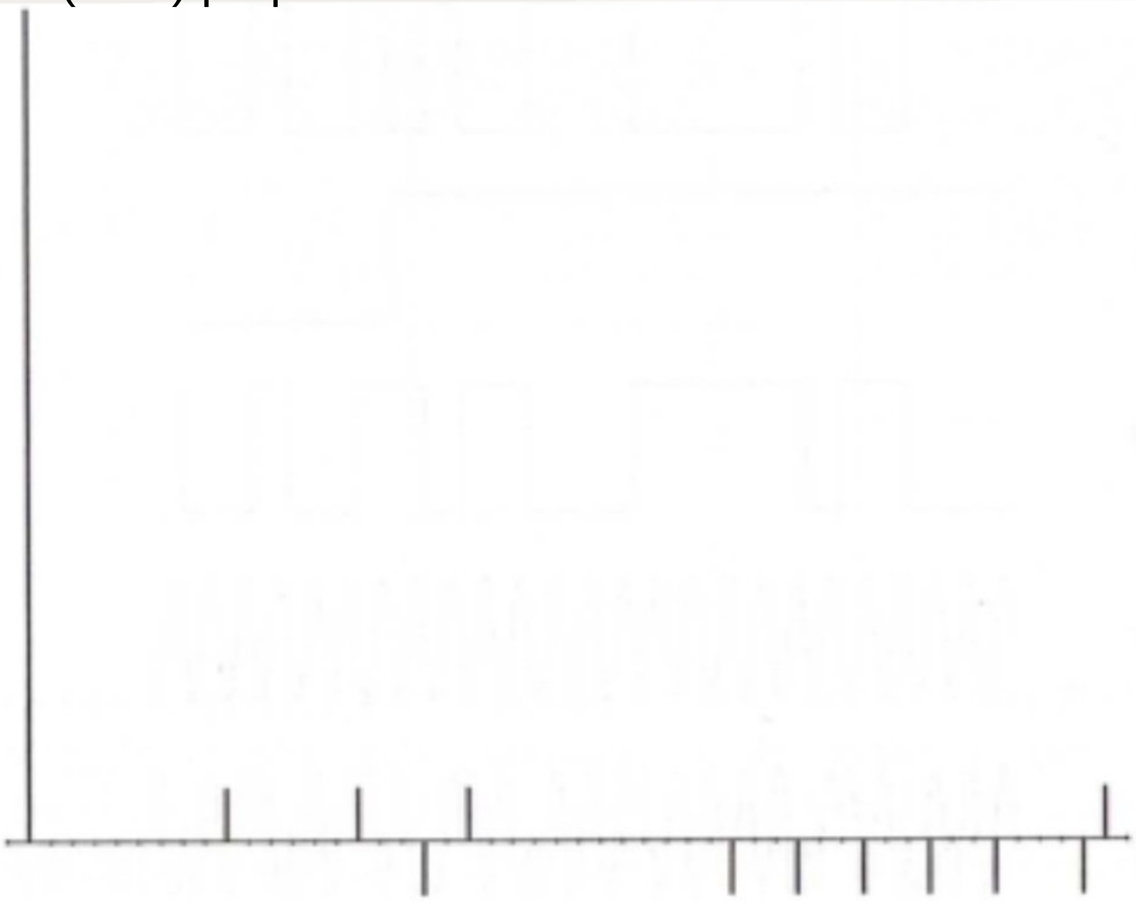

FIGURE 2.4. Stem plot of an ACF for a Gold sequence. The left stem has correlation value $r_p(0) = 1$; all other correlation values are $\frac{63}{1023}$, $\frac{-1}{1023}$, or $\frac{-65}{1023}$. Only the first 50 lags out of 1023 are shown.

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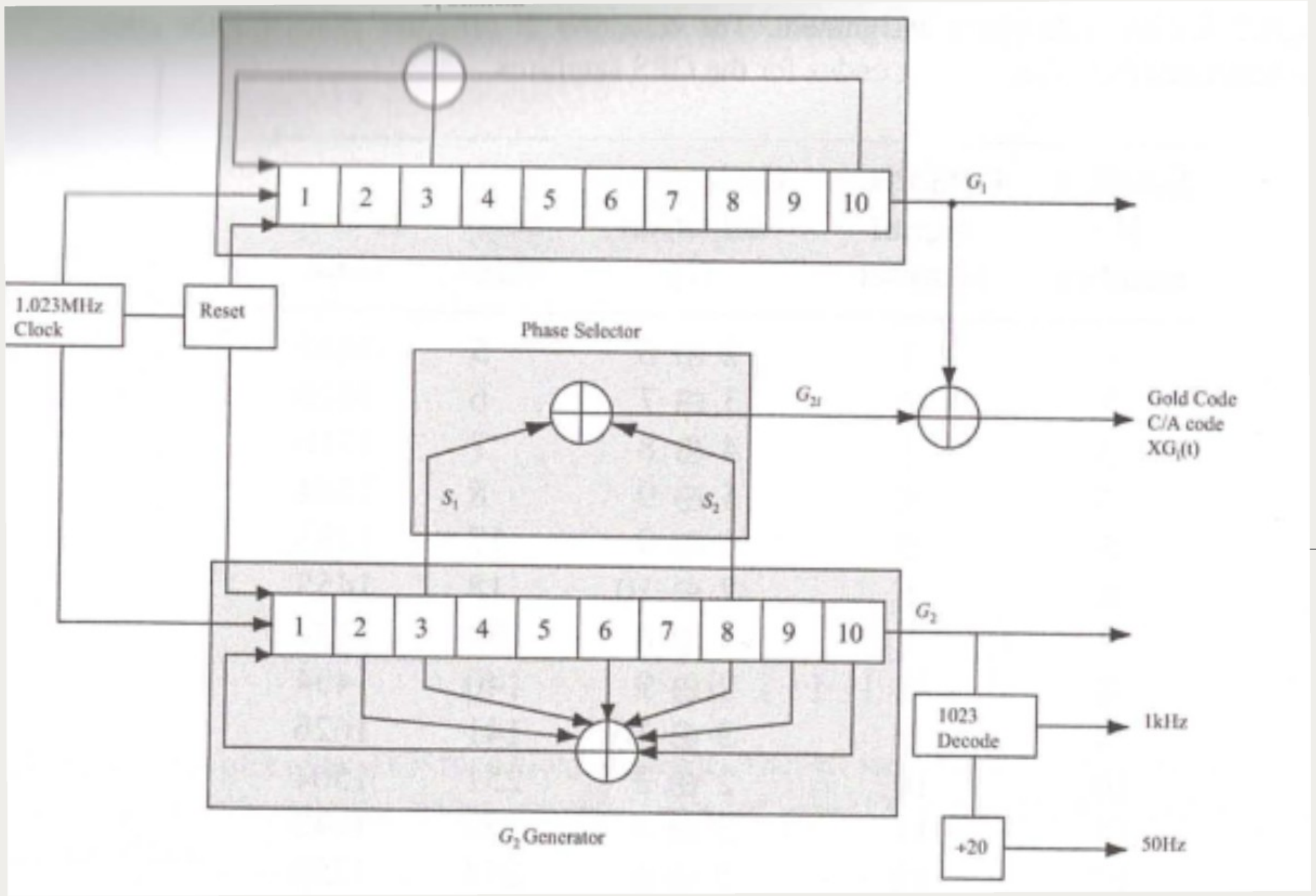
Genereren en ontvangen van DSSS

Pseudo-random noise / pseudo-random bit/’chip’ patronen

→ Direct Sequence Spread Spectrum signalen



Satellite ID number	GPS PRN signal number	Code phase selection G_2	Code delay chips	First 10 chips octal
1	1	2 ⊕ 6	5	1440
2	2	3 ⊕ 7	6	1620
3	3	4 ⊕ 8	7	1710
4	4	5 ⊕ 9	8	1744
5	5	1 ⊕ 9	17	1133
6	6	2 ⊕ 10	18	1455
7	7	1 ⊕ 8	139	1131
8	8	2 ⊕ 9	140	1454
9	9	3 ⊕ 10	141	1626
10	10	2 ⊕ 3	251	1504
11	11	3 ⊕ 4	252	1642
12	12	5 ⊕ 6	254	1750
13	13	6 ⊕ 7	255	1764
14	14	7 ⊕ 8	256	1772
15	15	8 ⊕ 9	257	1775
16	16	9 ⊕ 10	258	1776
17	17	1 ⊕ 4	469	1156
18	18	2 ⊕ 5	470	1467
19	19	3 ⊕ 6	471	1633
20	20	4 ⊕ 7	472	1715
21	21	5 ⊕ 8	473	1746
22	22	6 ⊕ 9	474	1763
23	23	1 ⊕ 3	509	1063
24	24	4 ⊕ 6	512	1706
25	25	5 ⊕ 7	513	1743
26	26	6 ⊕ 8	514	1761
27	27	7 ⊕ 9	515	1770
28	28	8 ⊕ 10	516	1774
29	29	1 ⊕ 6	859	1127
30	30	2 ⊕ 7	860	1453
31	31	3 ⊕ 8	861	1625
32	32	4 ⊕ 9	862	1712
—	33	5 ⊕ 10	863	1745
—	34	4 ⊕ 10	950	1713
[illegible]	35	1 ⊕ 7	947	1134
—	36	2 ⊕ 8	948	1456
—	37	4 ⊕ 10	950	1713

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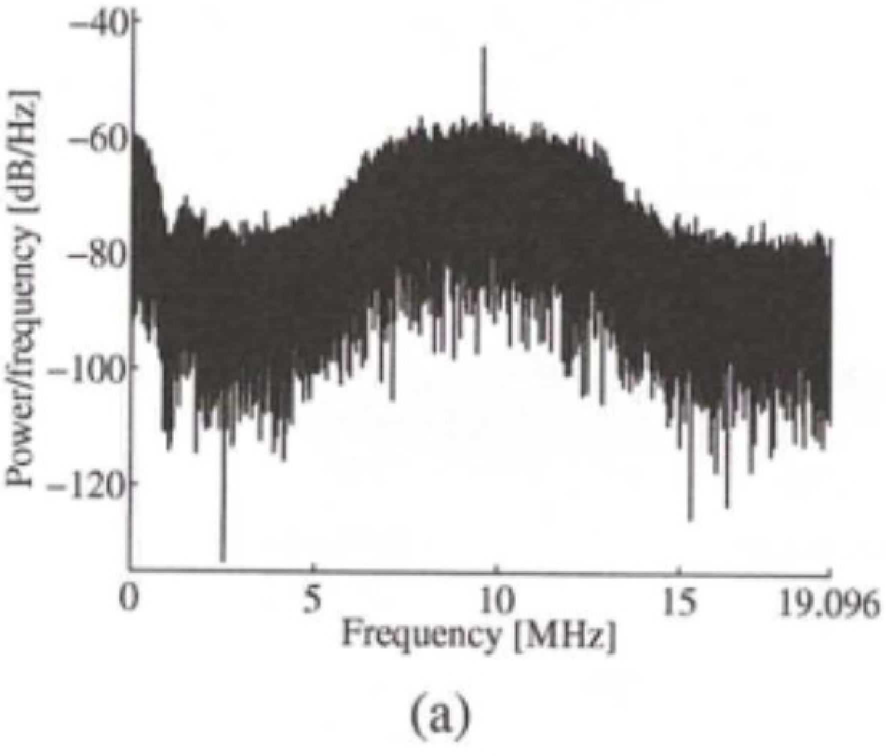

FIGURE 6.6. PSD plot of the incoming signal multiplied by a locally generated PRN code sequence. (a) When multiplying with a perfectly aligned PRN code, the output will show a peak at the carrier frequency. (b) When multiplying with a nonaligned code, the output will not show any peaks. The IF is 9.548 MHz. The Doppler frequency is the same on IF and RF, and thus also the difference between the IF and the peak frequency.

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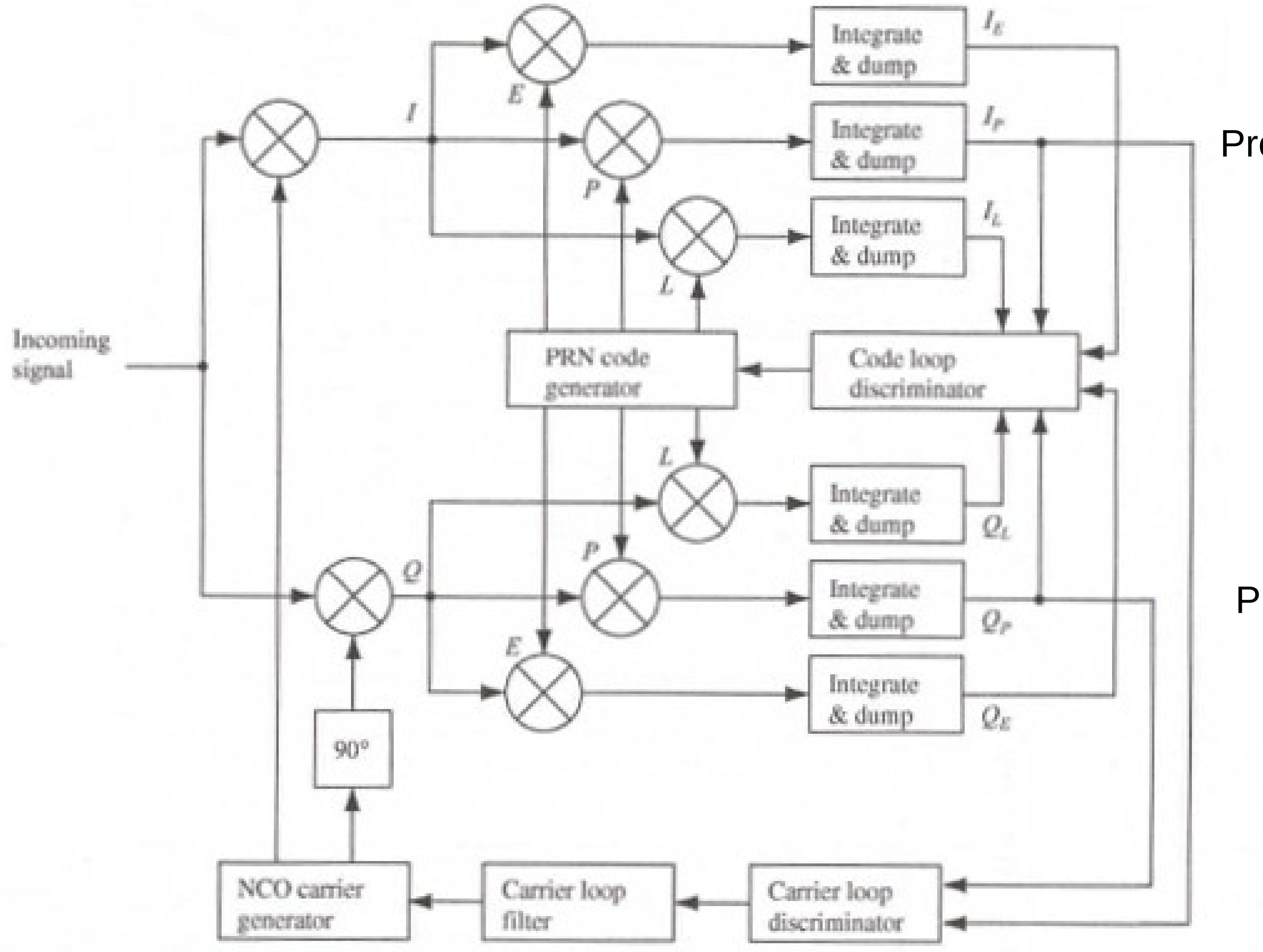

FIGURE 7.20. The block diagram of a complete tracking channel on the GPS receiver.

Early

Prompt (op tijd)

Late

Late

Prompt (op tijd)

Early

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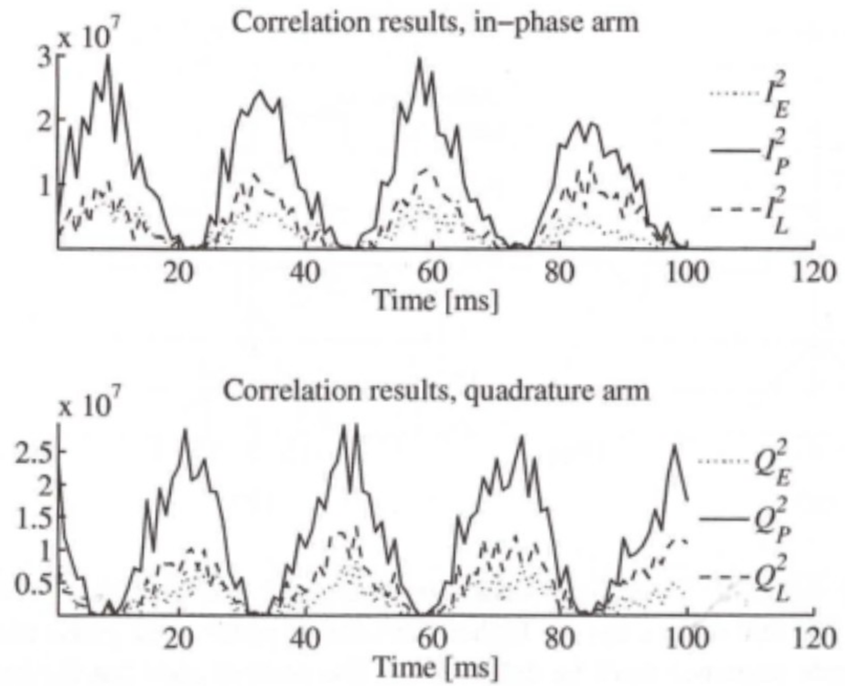

FIGURE 7.13. Output of the six correlators in the in-phase and quadrature arms of the tracking loop. Acquisition frequency offset is 20 Hz and PLL noise bandwidth is 15 Hz (for demonstration purpose).

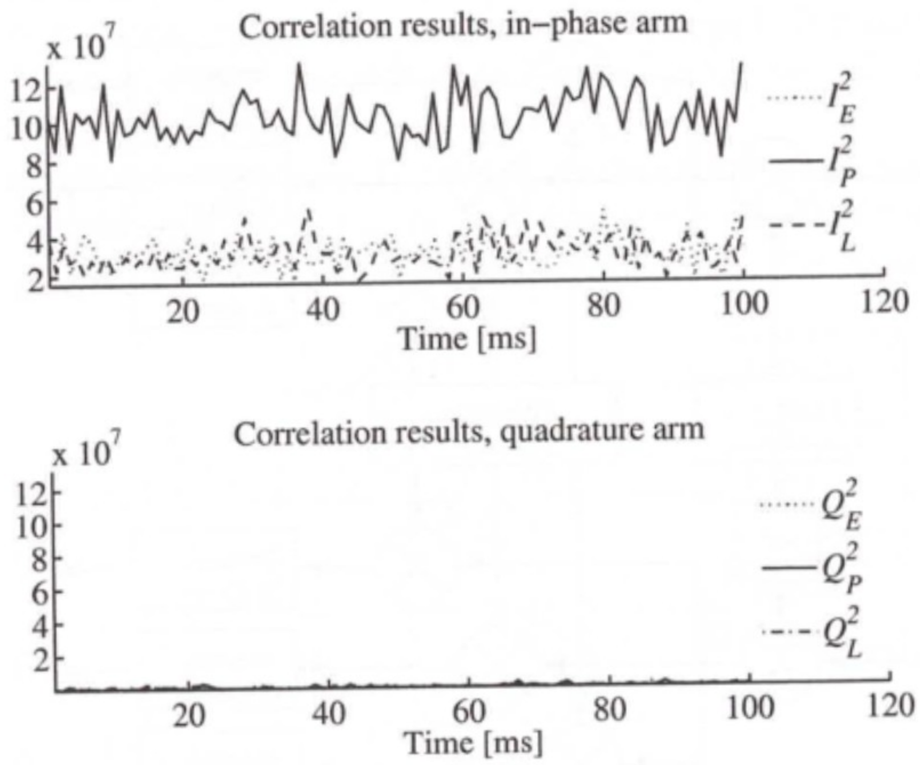

FIGURE 7.14. Output of the six correlators in the in-phase and quadrature arms of the tracking loop. The local carrier wave is in phase with the input signal.

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Alignment van code onder de ruis:
- Lock op een of meer msec aan PRN code, positieve of negatieve piek boven ruis
- Daarna zoeken naar (mogelijke) bit-transitie op exact 20 msec

- A-GPS met internet: veel bits zijn al van tevoren bekend
- A-GPS met 12.5 minuut aan goed ontvangen data van elke sateliet/alamanac:
  alle bits zijn bekend (tot er 2 uur om is en nieuwe data verwacht wordt)

RF Seminar

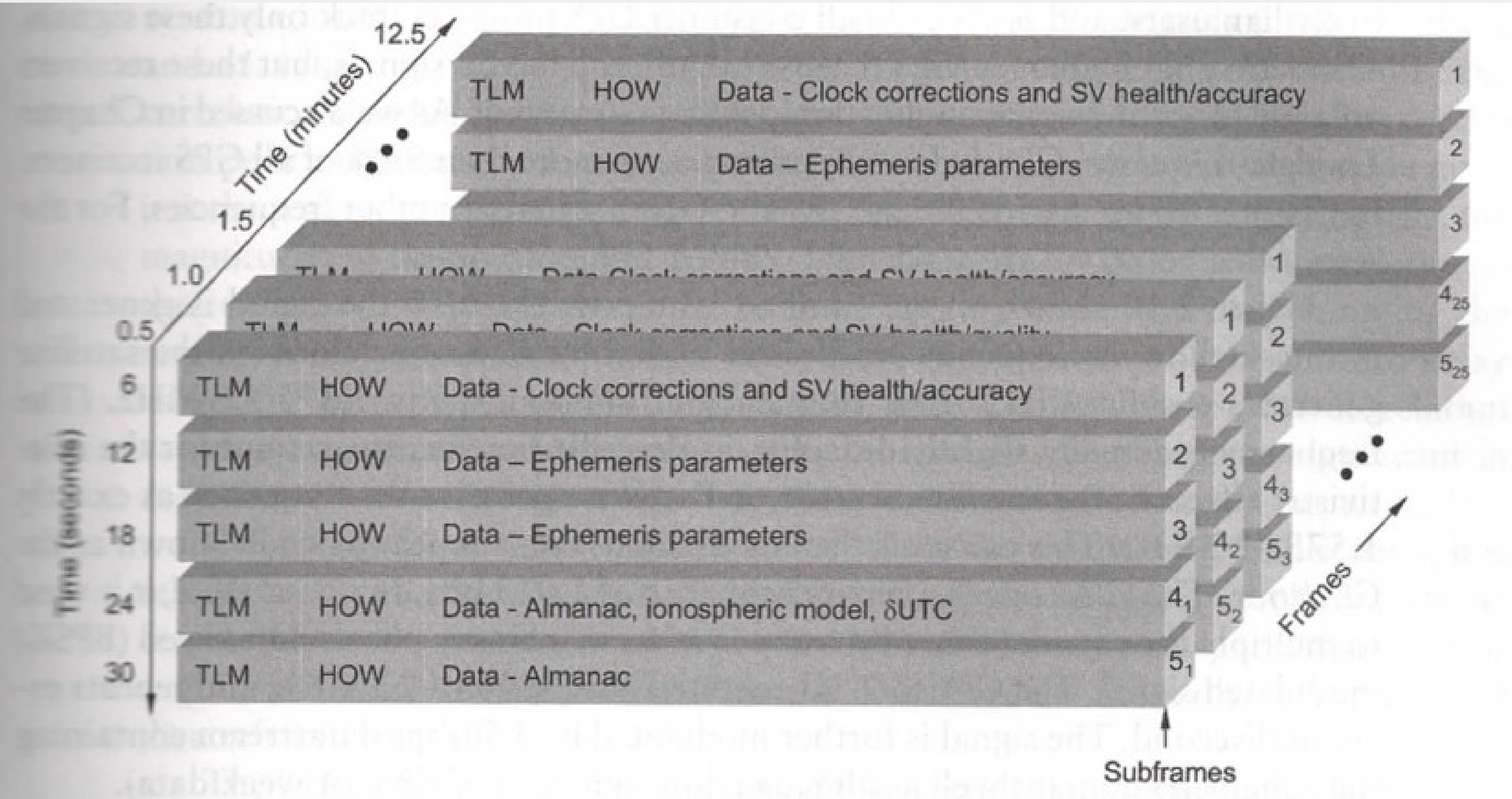

Figure 2.9 Broadcast data organization: frames, subframes, and words. Each subframe has ten words. Each word has 30 bits and takes 0.6s. Subframes 1, 2, and 3 repeat every 0.5 min; subframes 4 and 5 repeat every 12.5 min. Subframes 1, 2, and 3 are specific to the transmitting satellite; 4 and 5 are common to all satellites. Each subframe contains a time tag in the handover word (HOW), broadcast once every 6s. Ephemeris (plus clock corrections) is broadcast once every 30s. Each satellite broadcasts its own ephemeris. Almanac, ionospheric corrections, and UTC offset are broadcast in pieces, over 25 frames or 12.5 min. Each satellite broadcasts the complete almanac.

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Eisen aan ADC en front-end in het geval van smalbandige interferentie (CW, SSB, bijv @ 23 cm + E6)

RF Seminar

4.2.5 *Analog-to-Digital Converter*

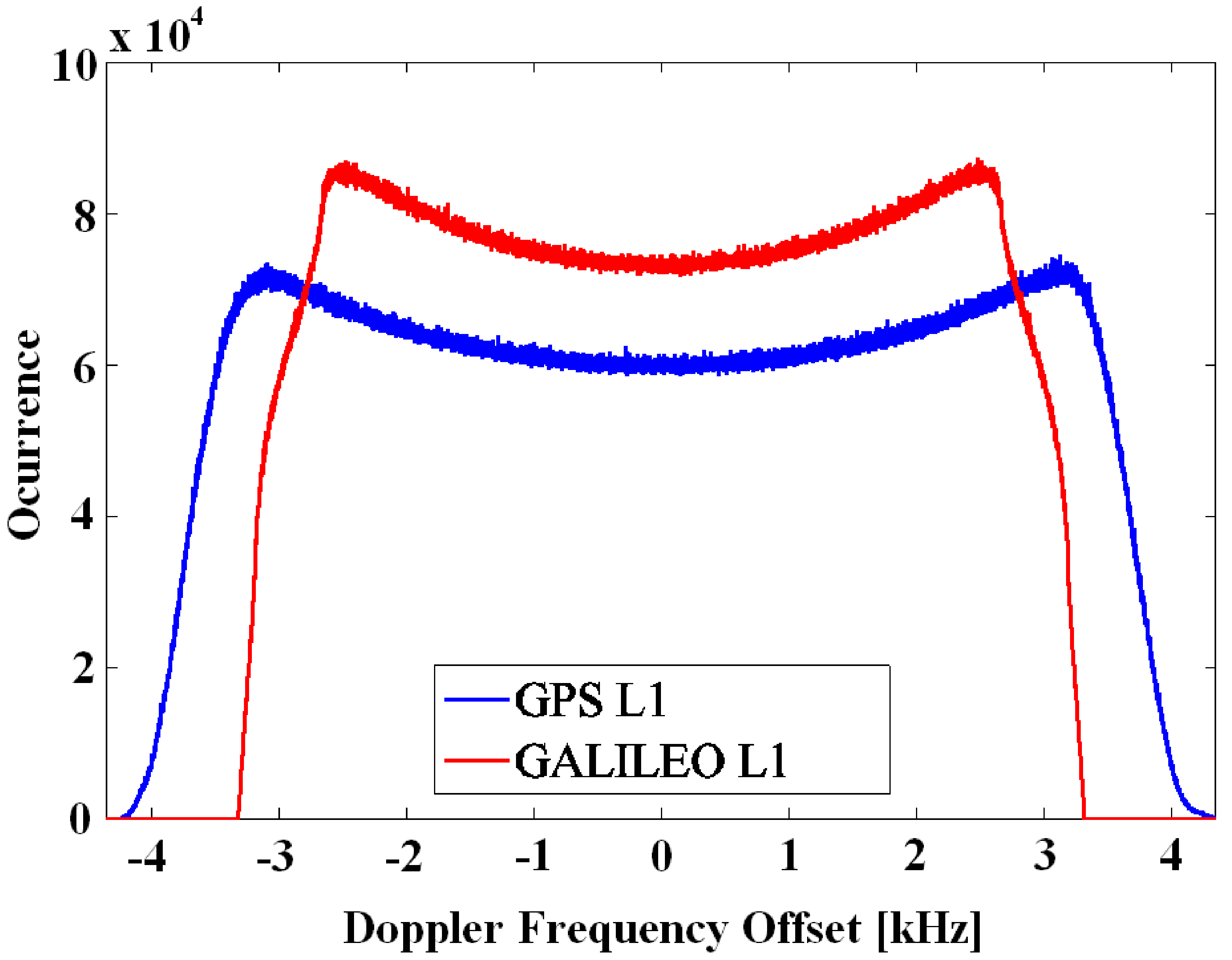
The final component in the front-end path is the analog-to-digital converter. This device is responsible for the conversion of the analog signal to digital samples. There is a wide variety of ADCs available on the market, with a dizzying set of parameters for each. Consider, for example, the Texas Instruments ADS830 ADC, see focus.ti.com/lit/ds/symlink/ads830.pdf. Such an ADC has an overwhelming number of parameters, the majority of which are not discussed here. An application note can help users sort out the various parameters associated with ADCs; see Anonymous (2000).

The key parameters to consider for this discussion are the *number of bits*, the *maximum sampling frequency*, the *analog input bandwidth*, and the *analog input range*.

The CDMA nature of the GNSS signal requires very little dynamic range from the sampled signal. It has been shown that if single bit sampling is used, then degradation in the resulting processing is less than 2 dB; see Bastide et al. (2003). Further, if conservative 2- or more bit sampling is utilized with proper quantization, the degradation is less than 1 dB. The minimum number of bits on most commercial ADCs is 8 as is the case for the ADS830. Thus, in designing a GNSS front end, it is most convenient to either utilize a hard limiter to obtain a single bit or use a commercial ADC taking all or just a subset of the resulting bits of each sample. It is also important to recognize that if multibit sampling is employed, then some form of gain control must be implemented to provide proper quantization.

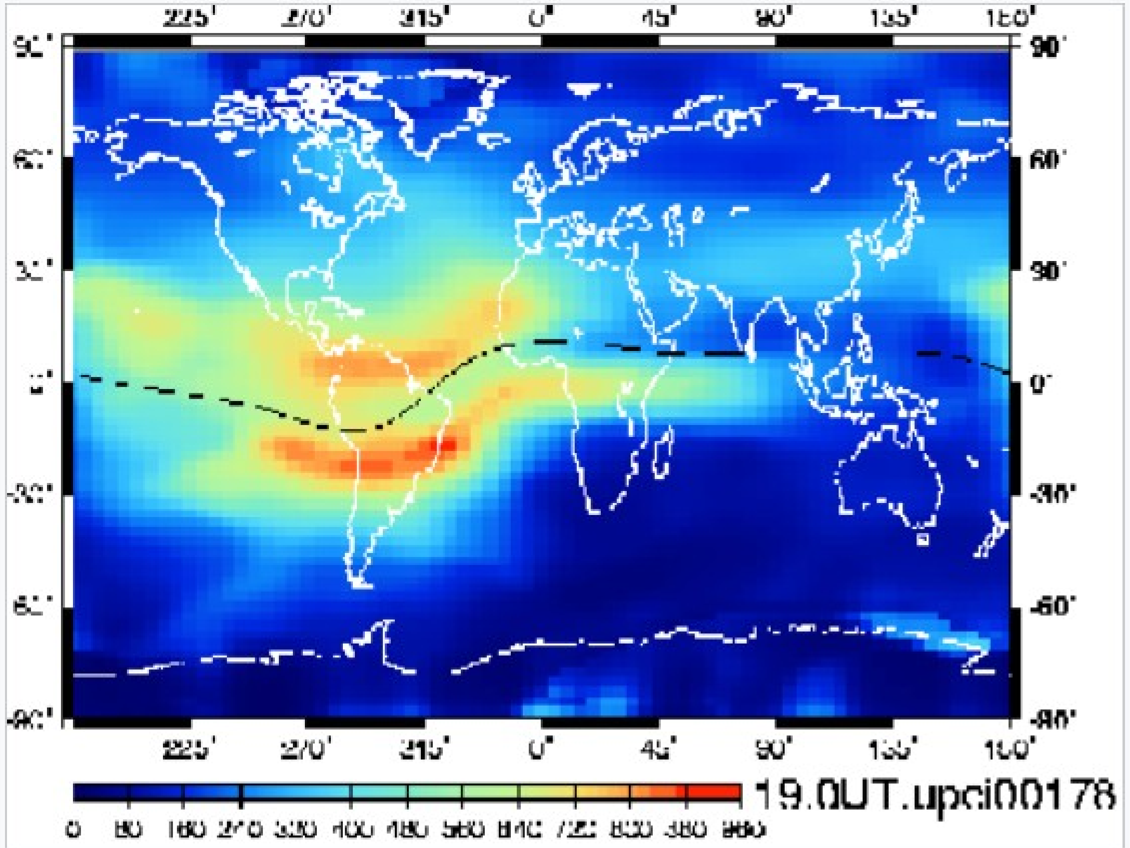
One might ask if the penalty for using single bit sampling is less than 2 dB, why any front end would utilize multibit sampling and then incorporate the overhead associated with automatic gain control? The key point to remember is that the less-than 2 dB penalty is for the ideal case. If, for example, there exists narrowband interference within the GNSS L1, then single bit sampling will be captured by the interference source and prevent GNSS processing. Thus, although the theoretical penalty for single-bit sampling is less than 2 dB, the nature of the operating environment may dictate the need for multibit sampling.

Bastide, F. Akos, D, Macabiau, C & Returier, B. (2003), Automatic Gain Control (AGC) as an interference assessment tool. In 16th International Technical Meeting of the Satellite Division of the Institute of Navigation, pages 2042-2053

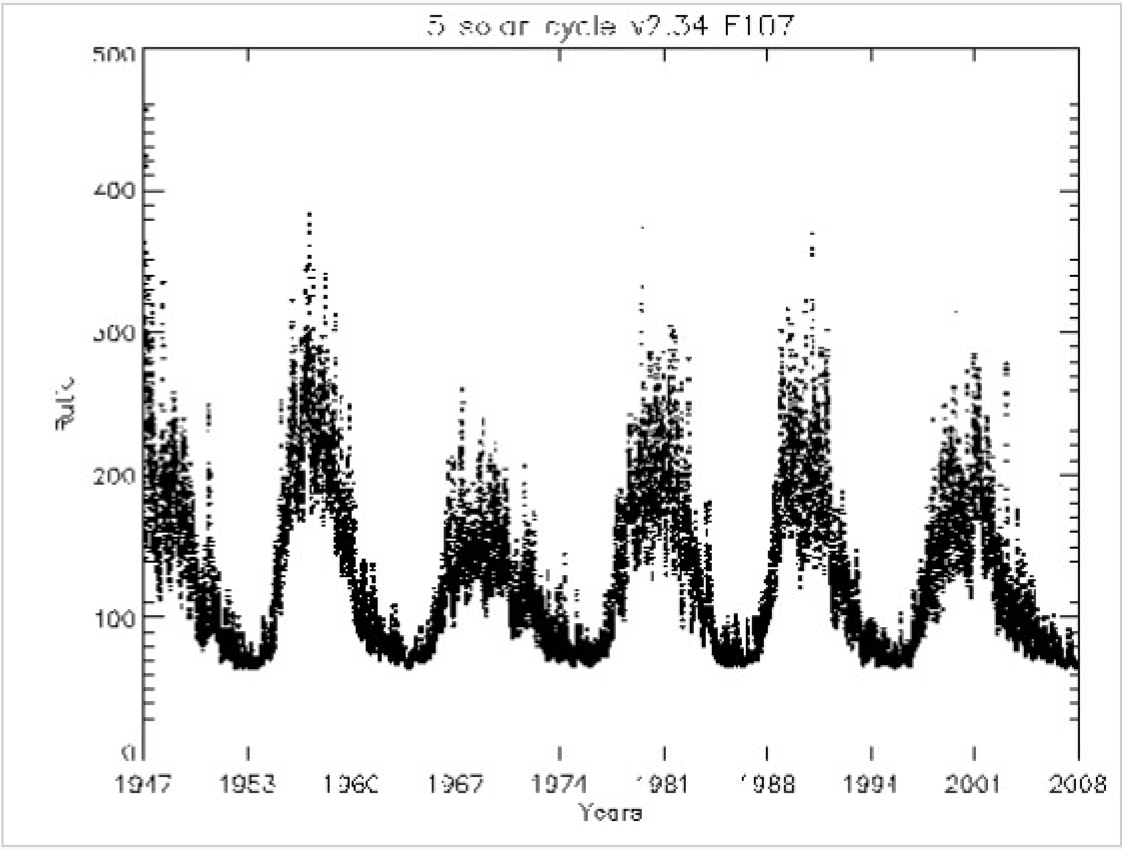


https://gssc.esa.int/navipedia/index.php/GNSS_Interference_Model

Range-Resolution: snelheid propagatie beinvloed door Total Electron Content tussen satelliet en antenne



frameless



frameless

Figure 1: Figure at left: Vertical Total Electron Content in units of $0.1\ TECUs \simeq 1.6\ cm$ *of delay in the GPS L1 signal at 19UT of the 26th of June of 2000. The plot at right shows the Solar flux evolution during the last solar cycles.*

Effecten van Multipath op GPS BPSK / Gold code en Galileo BOC codes

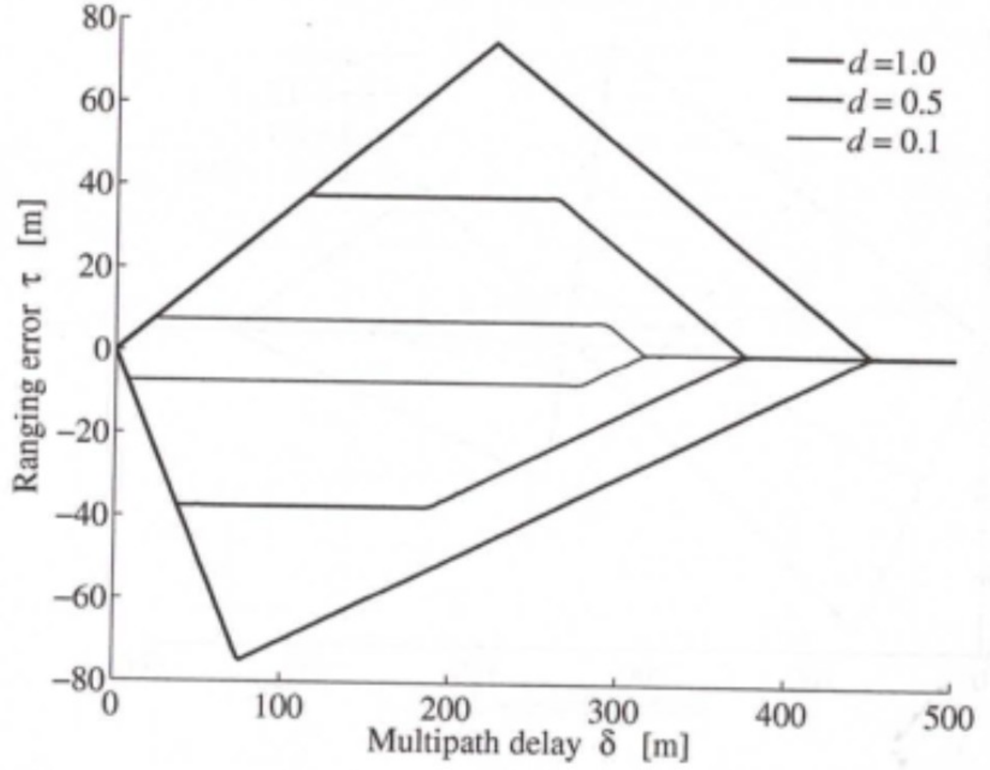


FIGURE 7.17. Multipath error envelope for noncoherent early/late detector for C/A code, $\alpha = 0.5$. The positive multipath error corresponds to constructive interference while negative multipath error corresponds to destructive interference.

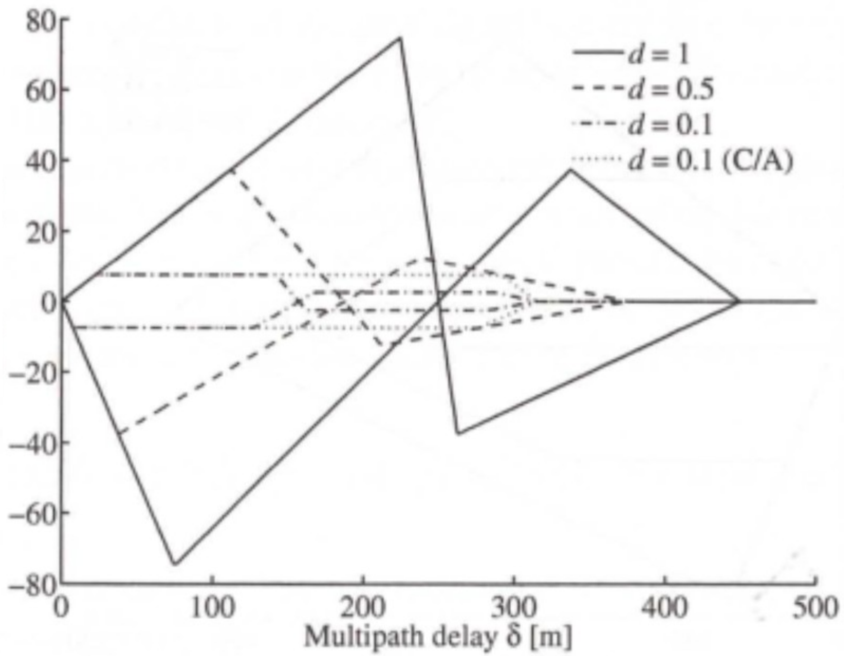


FIGURE 7.18. Multipath error envelope for noncoherent early/late detector for BOC(1,1). Negative ranging error corresponds to destructive interference.

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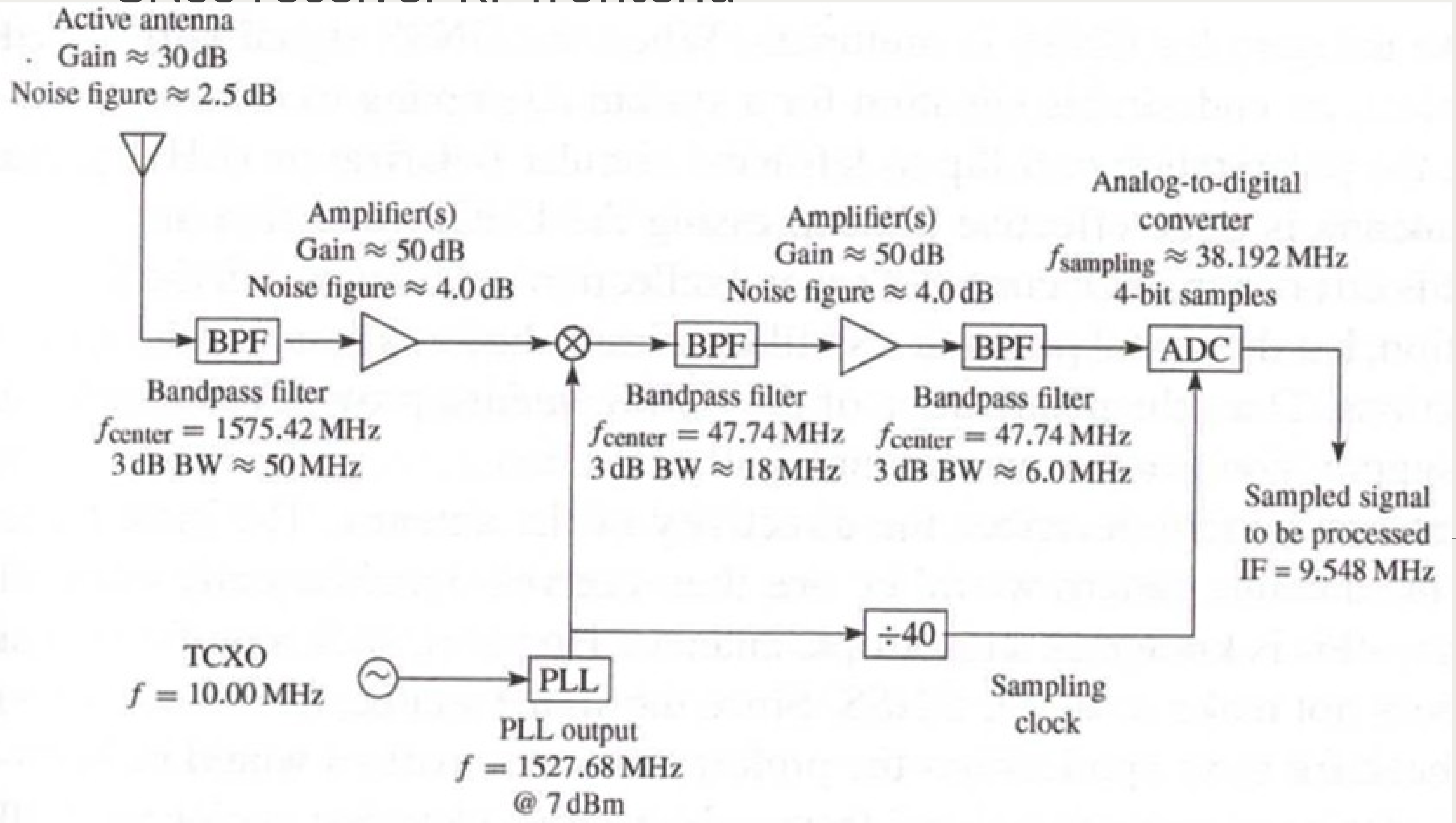
- GPS RF frontends keuze
- Voor oplossingen zonder module (zelf alle processing doen)

- GNSS receiver RF frontend



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- Implementatie van GNSS receiver front-end

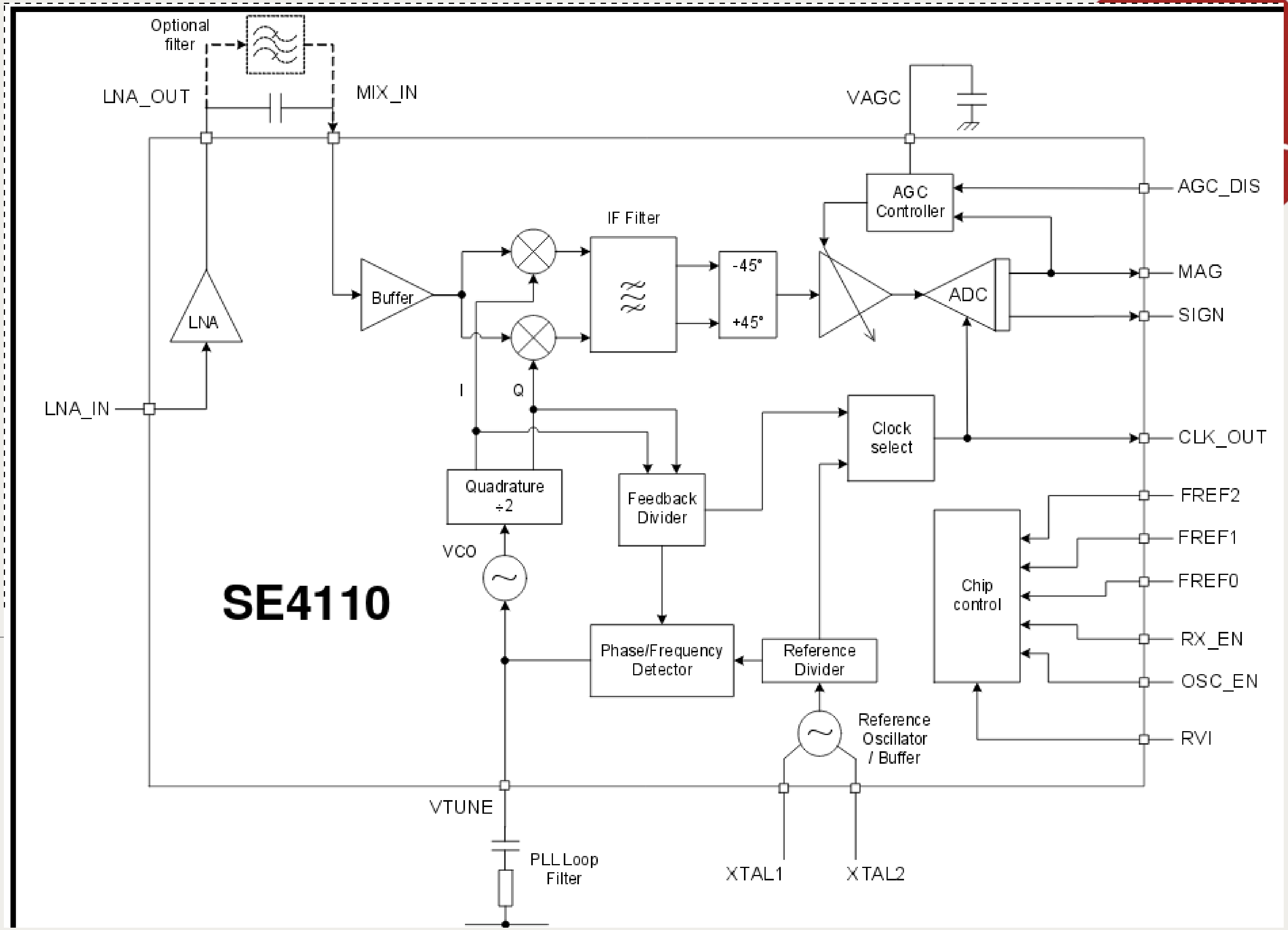
- Discreet: Andrew Holme's Homemade GPS Receiver (September 2014 GPL)

- Single-chip RF frontend: stabieler, I/Q sampling en multi-bit ADC (0 en 90 deg LO) mogelijk
- Volledige controle over software-definieerbare aspecten van GNSS ontvangst

Ontvangers zonder module, met, open-source of zelfontwikkelde software:

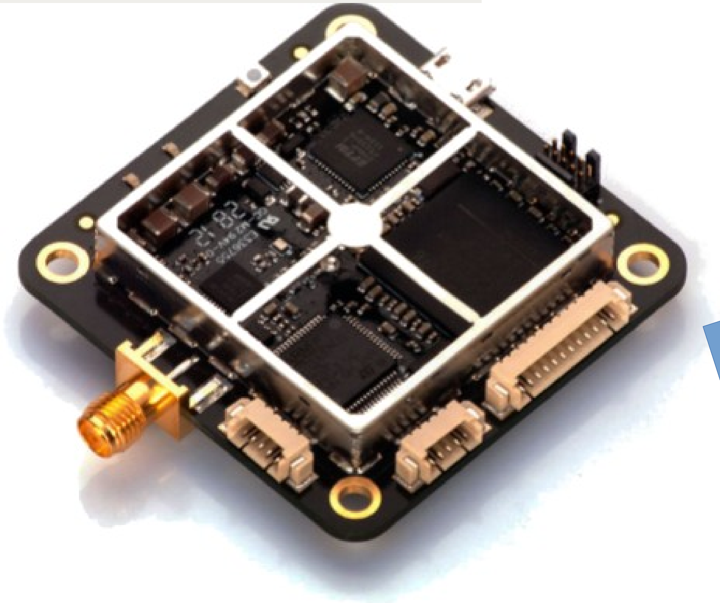
- Swift-nav Piksi receiver (2013): Maxim MAX2769 + Xilinx Spartan-6 FPGA + STM32 Cortex M4 microcontroller + open-source software. FPGA firmware/filters/correlators proprietary.
- KIWI-SDR Beagle-bone shield: Skyworks RF frontend

- SiGe SE4110L (2006)
- Automatic gain control
- Dynamic Range



https://ccar.colorado.edu/gnss/files/SE4110L_Datasheet_Rev3.pdf

Swift-Nav Piksi Commercieel, Open-Source GPS L1 receiver (Kickstarter 2013, Colin Beighley en Fergus Noble)



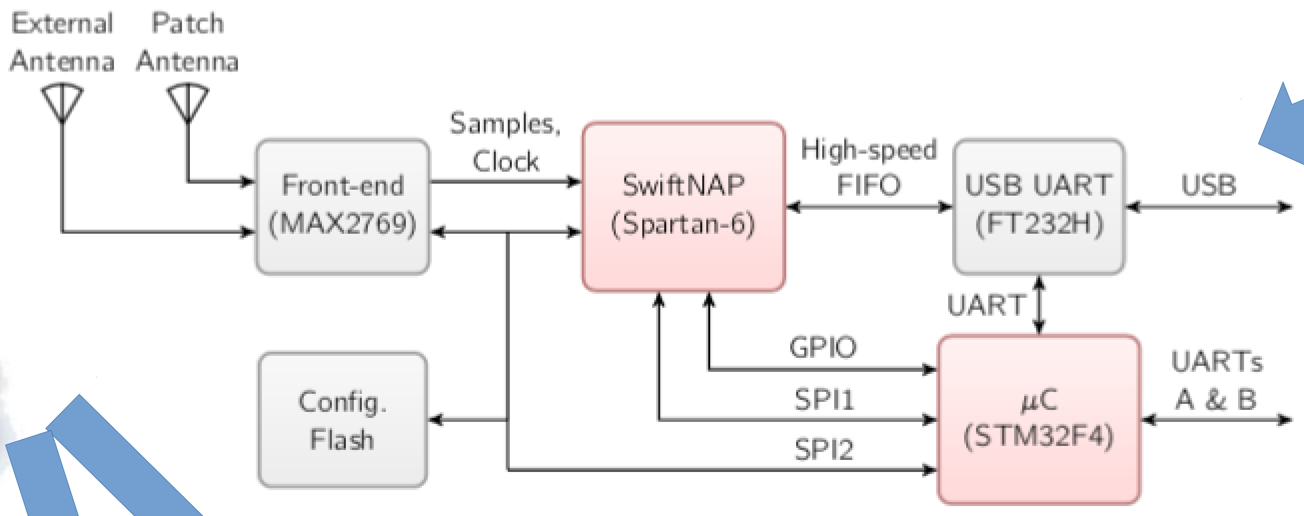
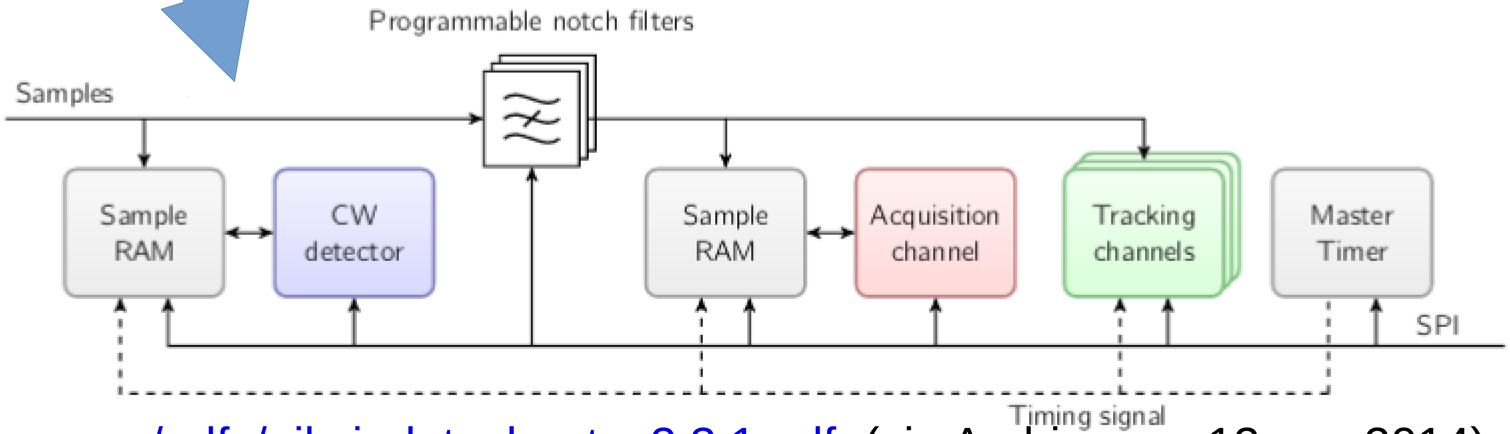


Figure 2: Piksi Block Diagram

Doel: GPS RTK met L1 band signalen, rover en base, differential pseudo-ranges

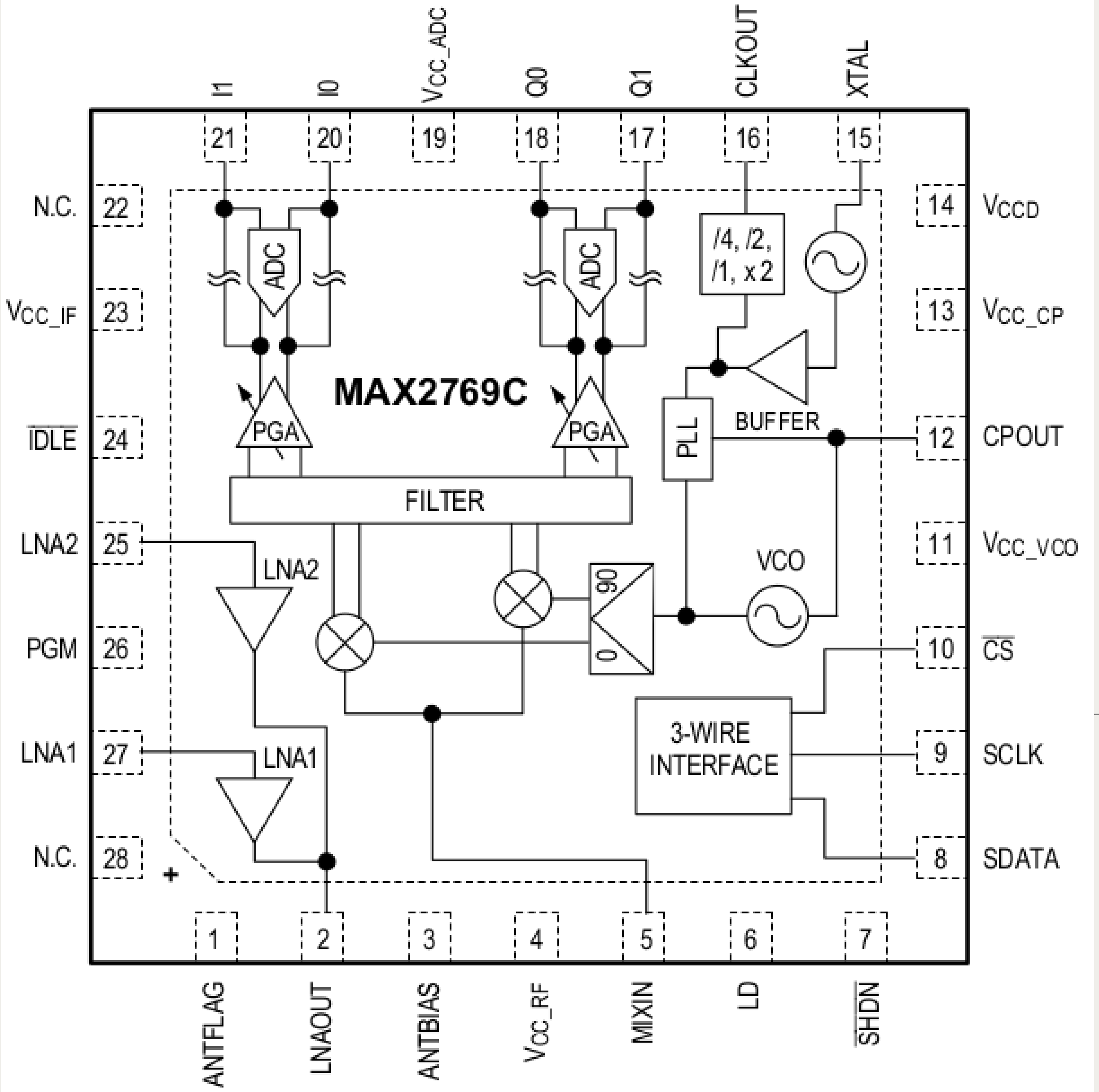
STM32F4 + FPGA + Maxim

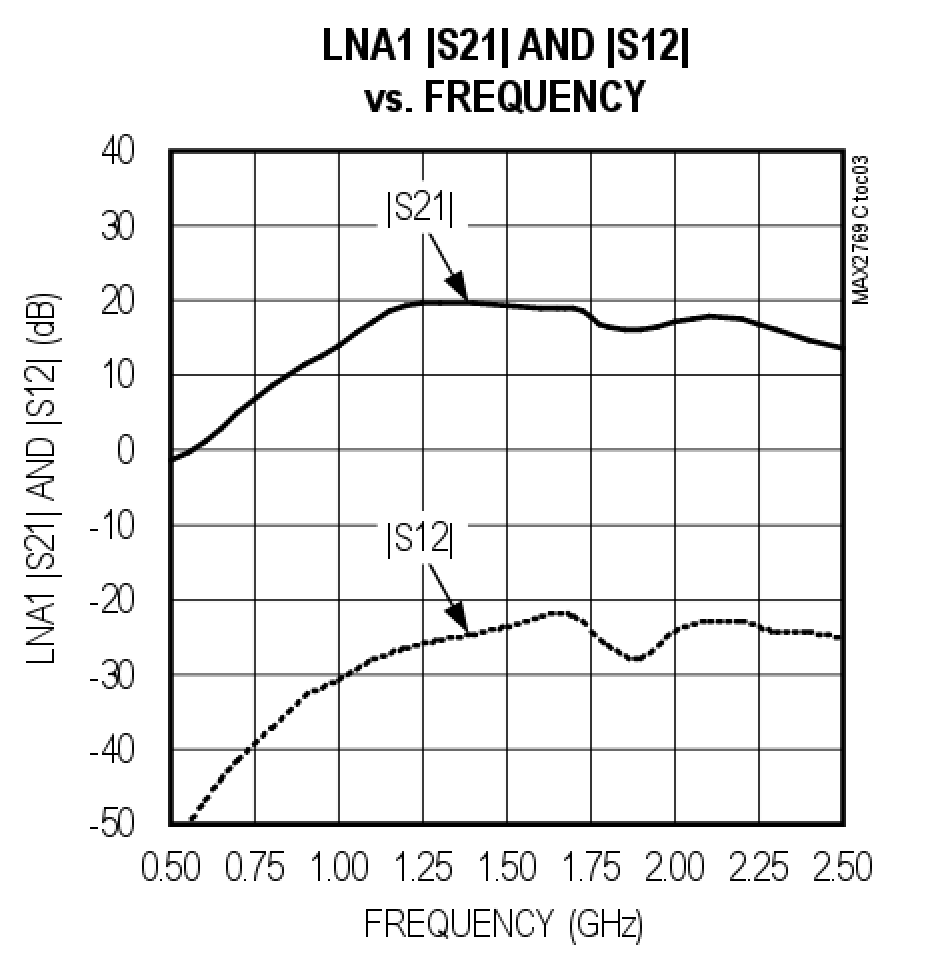


Bron: https://docs.swiftnav.com/pdfs/piksi_datasheet_v2.3.1.pdf (via Archive.org 12 sep 2014)

Figure 3: SwiftNAP Block Diagram

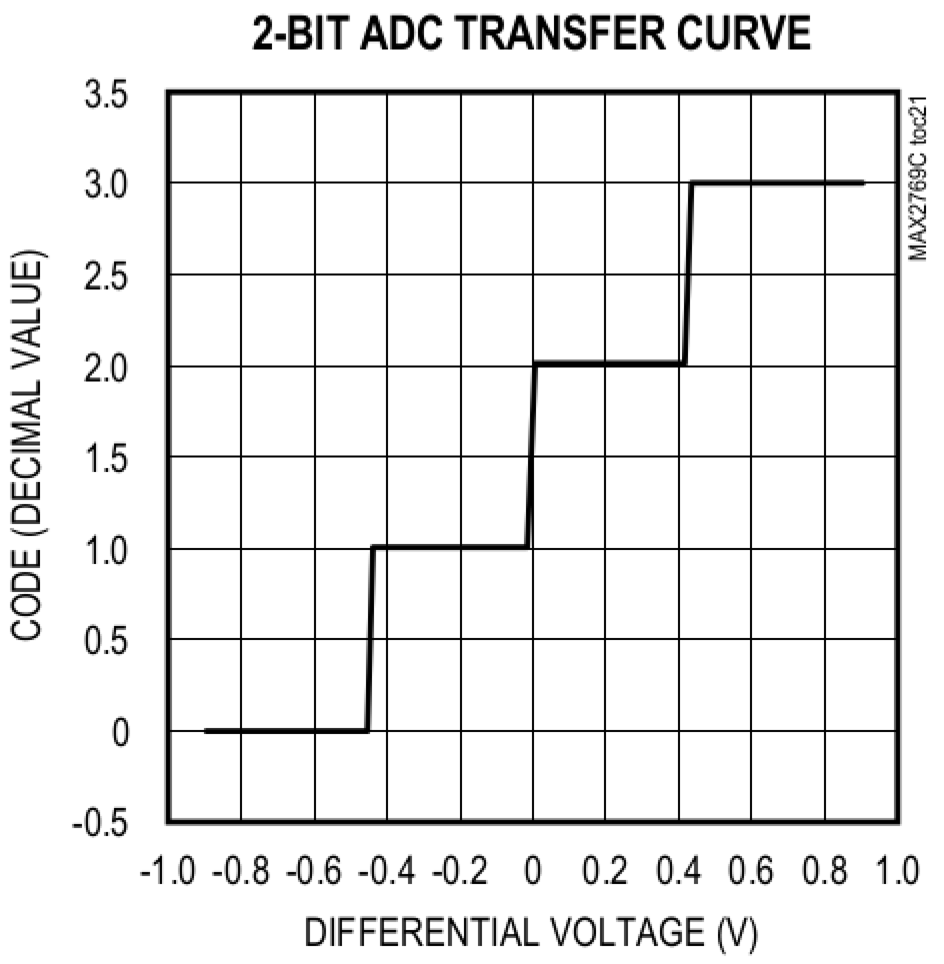
- Swift-Nav Piksi: Maxim MAX2769C

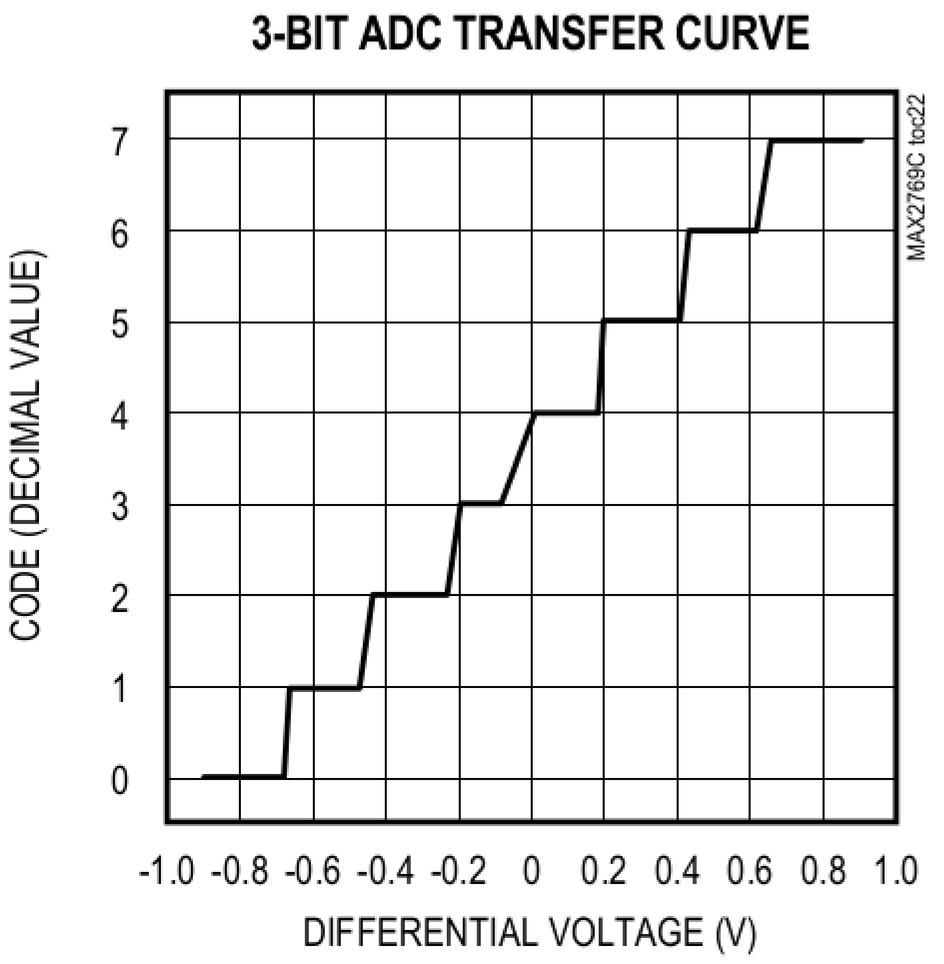




https://datasheets.maximintegrated.com/en/ds/MAX2769C.pdf

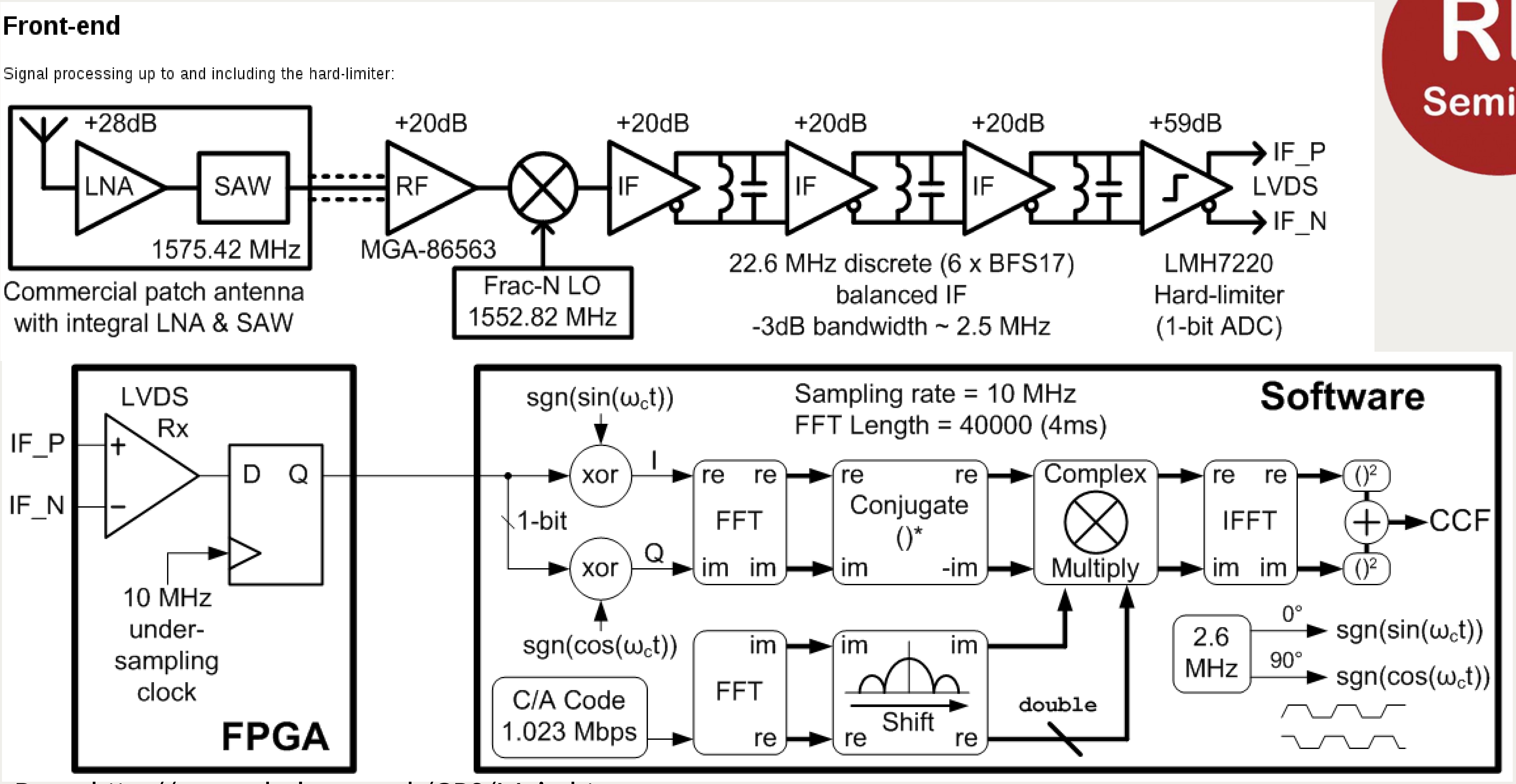
Swift-Nav Piksi: MAX2769C multi-bit digitizer: nauwkeurigheid



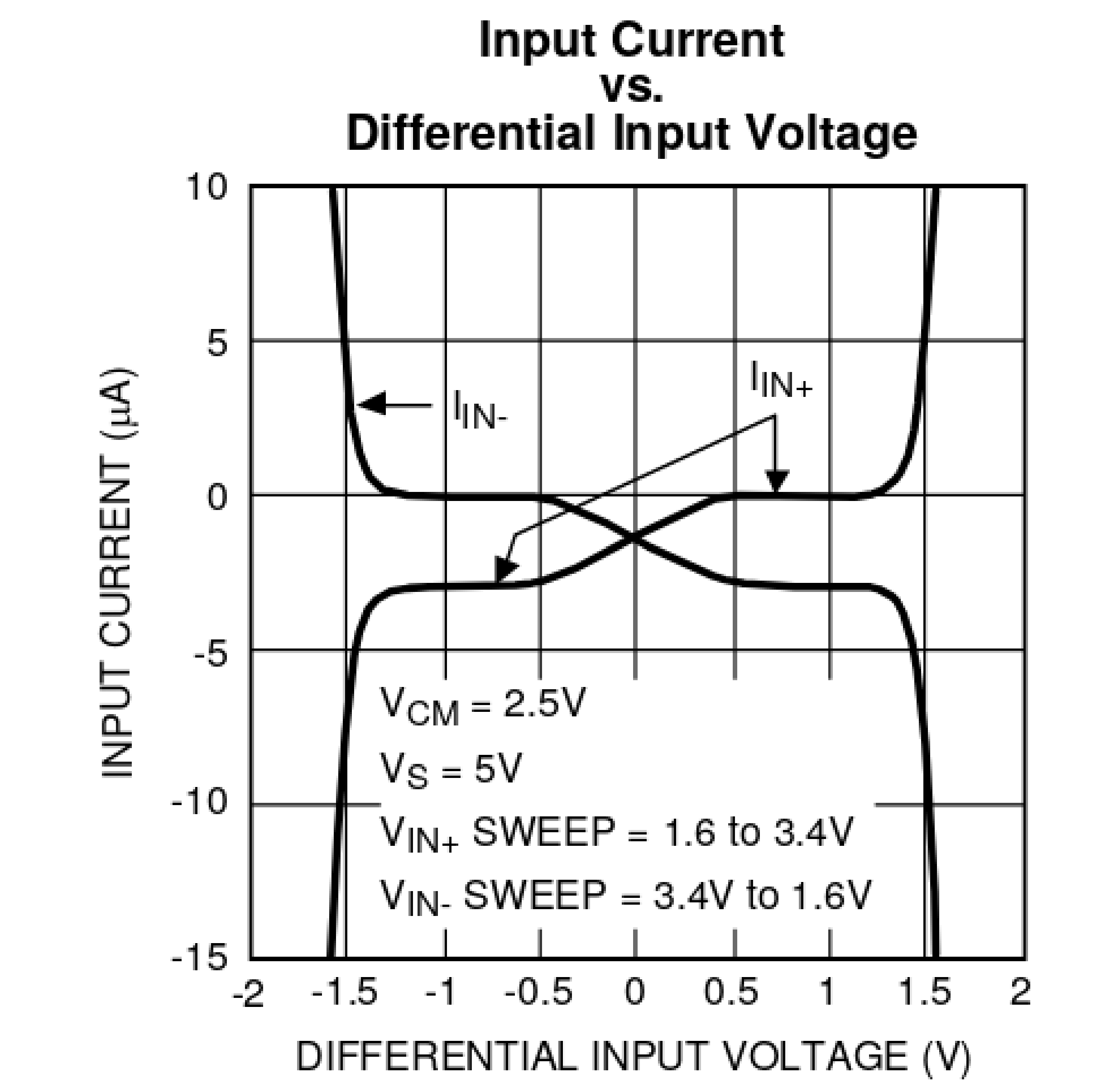


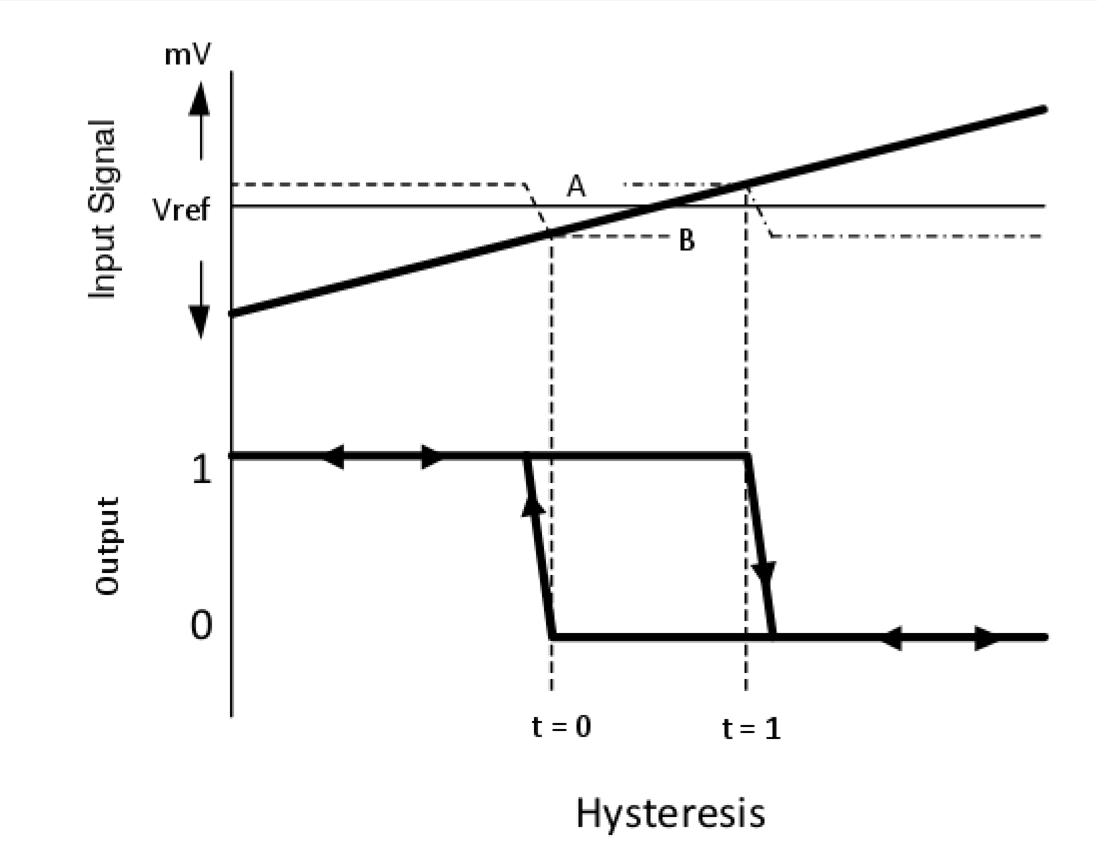
https://datasheets.maximintegrated.com/en/ds/MAX2769C.pdf

- Andrew Holme's homebrew GPS receiver (May 2013)



Bron: http://www.aholme.co.uk/GPS/Main.htm

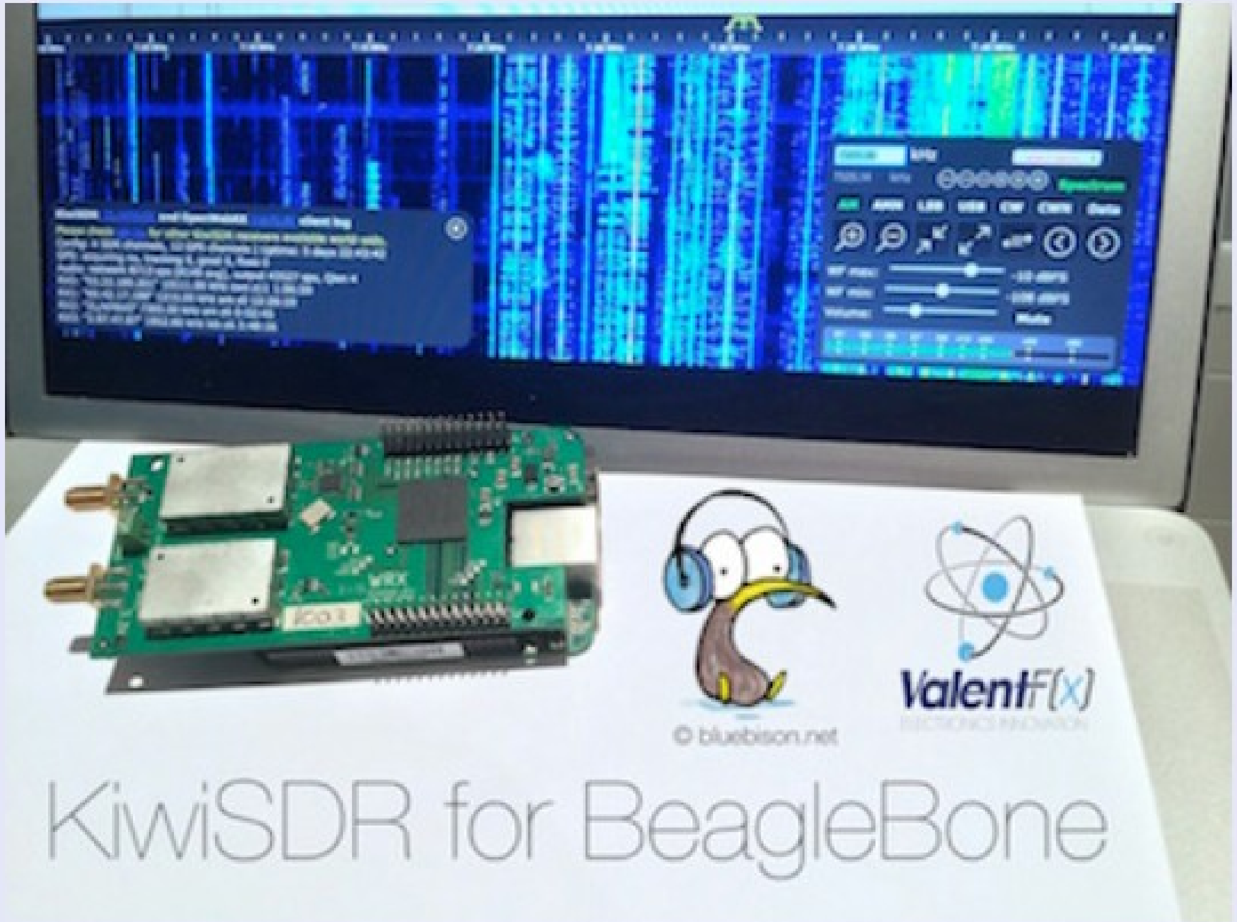




https://www.ti.com/lit/ds/symlink/lmh7220.pdf

- KiwiSDR.com (Maart 2016)

KiwiSDR: Wide-band SDR + GPS cape for the BeagleBone Black



- Hardware en software voor KiwiSDR GNSS ontvanger
- Tracking: Correlator based approach (weinig FPGA resources)
- Code search: Beaglebone software (FFT/IFFT methode)

6.4.2 GPSDO possibilities

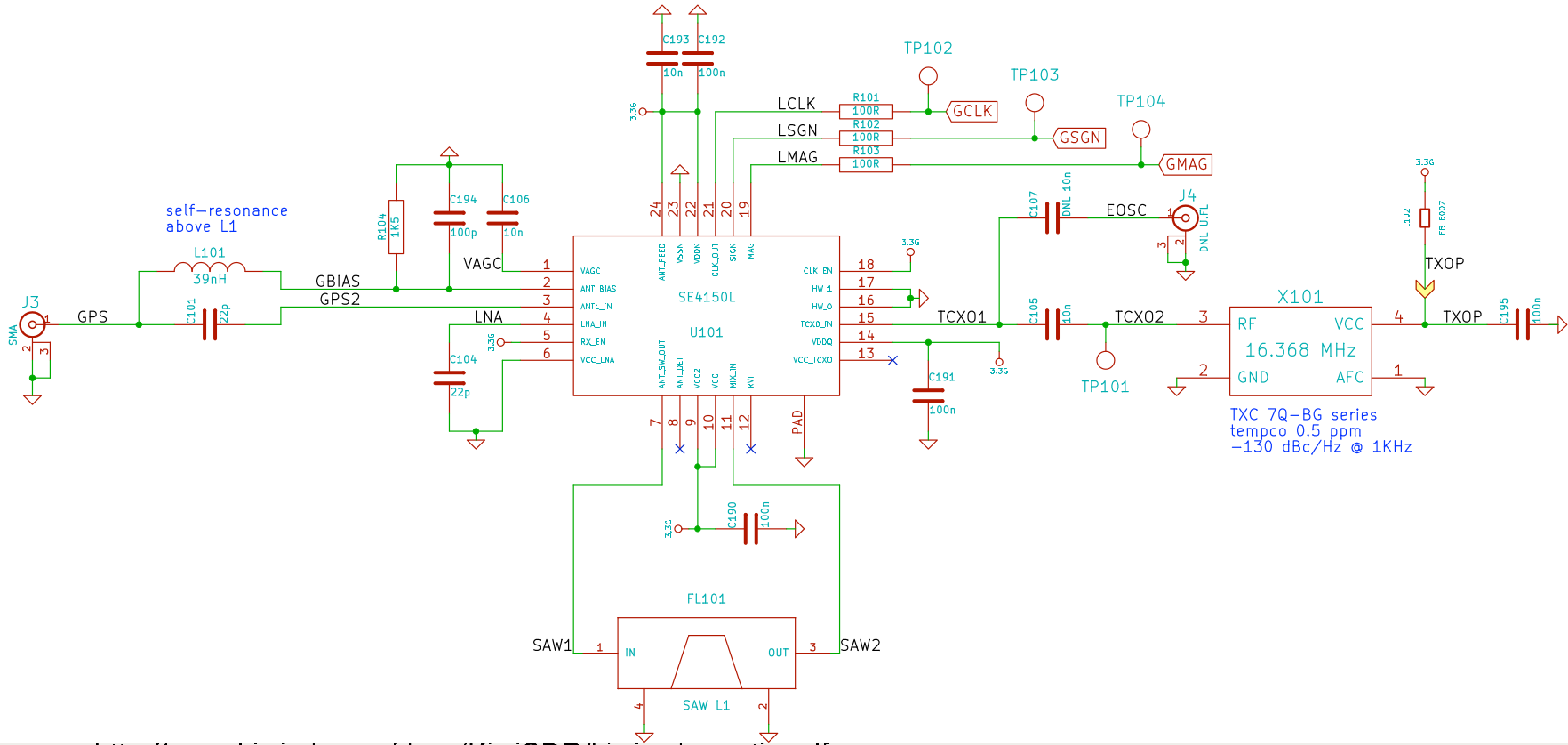
If anyone knows of some simple hardware changes that could be made to enable actual GPSDO experimentation I'd really like to know. There is a DNL U.FL connector and coupling cap for supplying an external clock input. But any experimentation is probably limited by the quality of the L1 PLL inside the chip. But I don't understand enough about GPSDO issues to know.

Questions:

- Any opinions about this from you GPSDO experts?

http://kiwisdr.com/docs/KiwiSDR/KiwiSDR.design.review.pdf

John Seamons Kiwi-SDR frontend: Skyworks SE4150, FL101 SAW filter, 16.368 MHz TCXO



http://www.kiwisdr.com/docs/KiwiSDR/kiwi.schematic.pdf

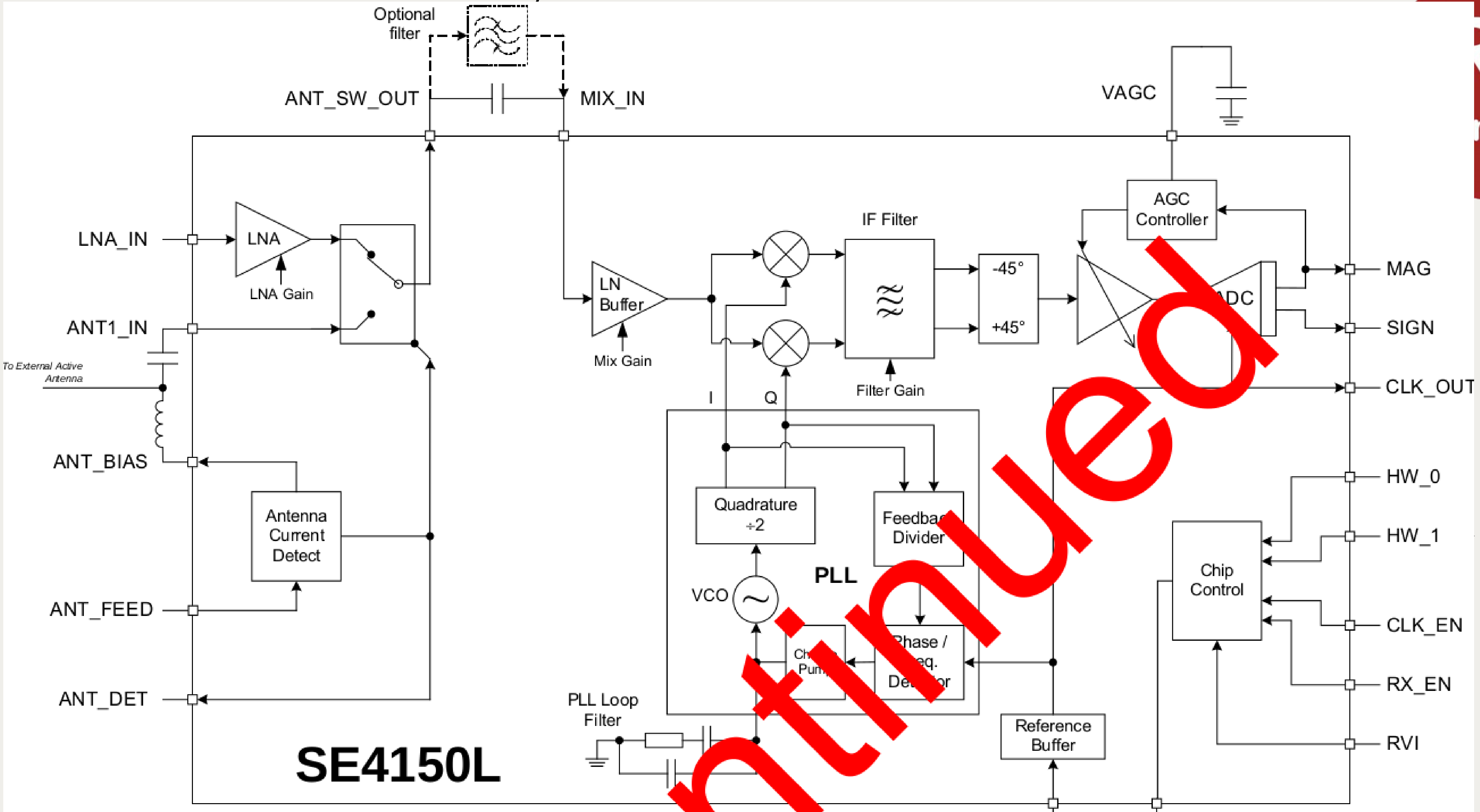
- SAW filter ‘FL101’
- Geen bijpassende datasheet gevonden

  Mogelijke alternatieven

  Mouser: 2..3 MHz bandbreedte 1575.42 MHz
- Abracon AFS20A02-1575.42-T3 2 MHz
- RF360/Epcos B39162B9417K610 2 MHz January 23, 2009
- EOL RF360/Qualcomm B39162B4060U810 January 31, 2013

  Digikey:
- Kyocera SF14-1575F5UUA1 3MHz
- Taiyo Yuden F6KA1G575L4AJ-Z 2 MHz
- Enkele varianten Kyocera/Taiyo Yuden

KiwiSDR/John Seamons RF Frontend: Skyworks SE4150



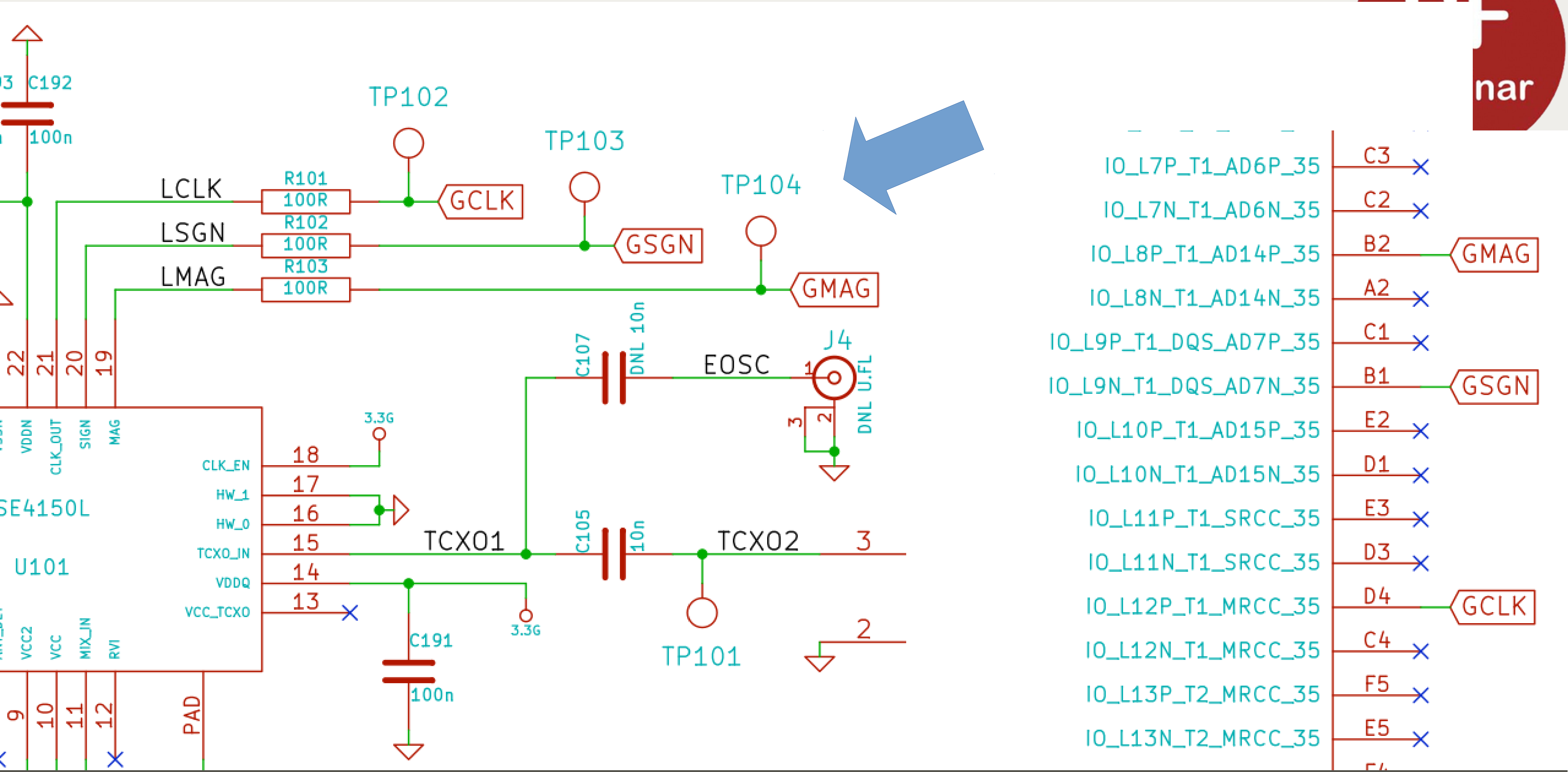
https://media.digikey.com/pdf/Data%20Sheets/Skyworks%20PDFs/SE4150L_DS.pdf

RF Seminar

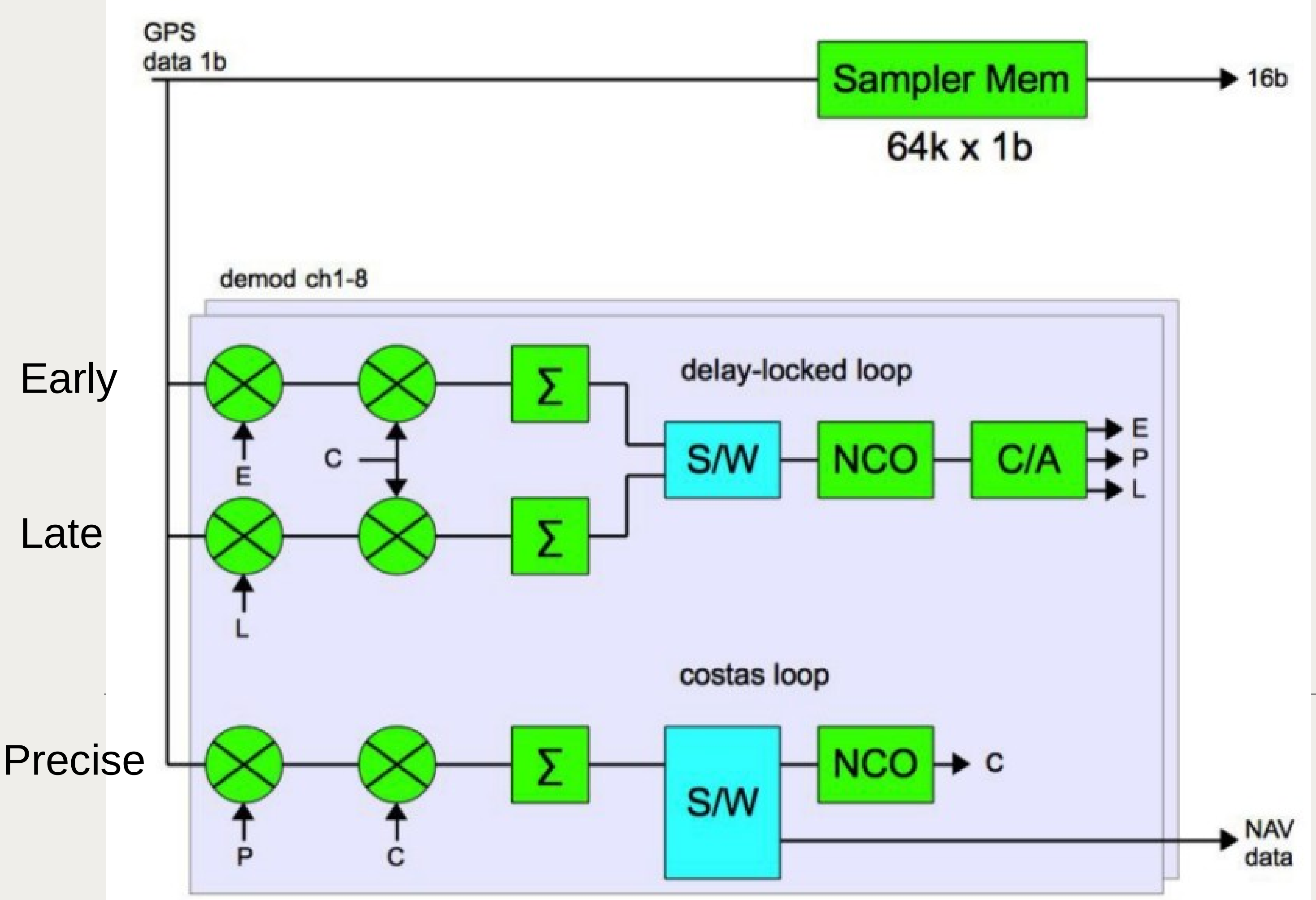
Compare Parts		Image	Digi-Key Part Number	Manufacturer Part Number	Manufacturer	Description	Quantity Available ?	Unit Price USD	Minimum Quantity	Packaging
			863-1354-2-ND	SE4150L-R	Skyworks Solutions Inc.	RF RECEIVER GPS 1575.42MHZ 24QFN	12,000 - Factory Stock ?	Obsolete	-	Tape & Reel (TR) ? Alternate Packaging
			863-1354-1-ND	SE4150L-R	Skyworks Solutions Inc.	RF RECEIVER GPS 1575.42MHZ 24QFN	7,218 - Immediate 12,000 - Factory Stock ?	$3.05000	-	Cut Tape (CT) ? Alternate Packaging
			863-1354-6-ND	SE4150L-R	Skyworks Solutions Inc.	RF RECEIVER GPS 1575.42MHZ 24QFN	7,218 - Immediate 12,000 - Factory Stock ?	Digi-Reel®	-	Digi-Reel® ? Alternate Packaging
	-	Digi-Key Photo Not Available	SE4150Z-W-ND	SE4150Z-W	Skyworks Solutions Inc.	RF IC'S + MODULES GPS	0	Obsolete	-	Bulk ?

https://www.digikey.com/products/en?keywords=SE4150

KiwiSDR/John Seamons post-processing FPGA



- Maar in hardware vooral alles 1-bit…



GPS:
acquisition data sampler &
tracking demod channels

Kristal uit KiWi SDR design review (2016)

RF Seminar

3.3V LVCMOS Surface Mount Crystal Clock Oscillator CWX823

In Stock at Digi-Key

CONNOR WINFIELD

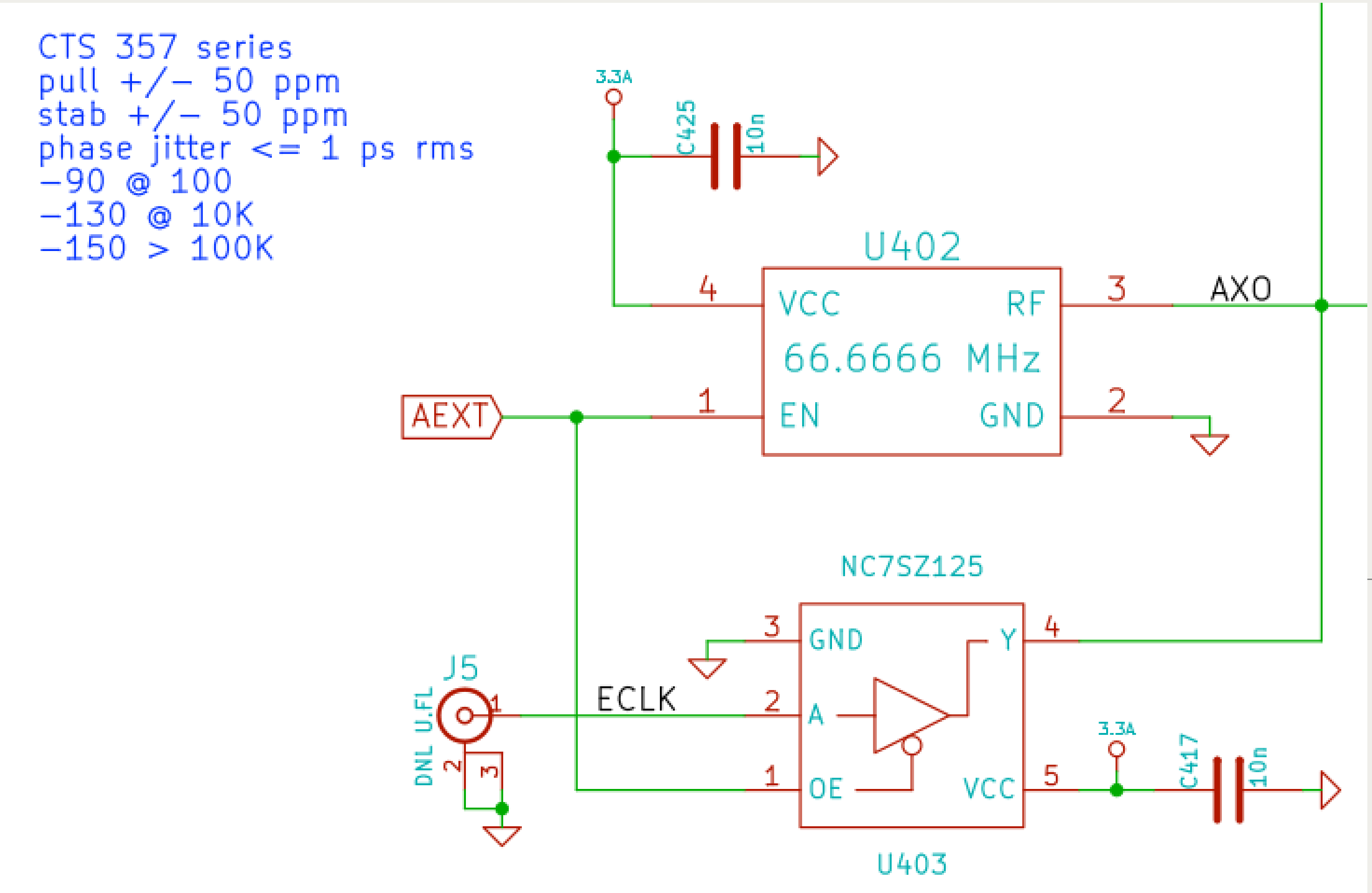
Input Characteristics

Parameter	Minimum	Nominal	Maximum	Units	Notes
Enable Voltage - (Vih)	≥ 2.2	-	-	Vdc	2
Disable Voltage - (Vil)	-	-	≤ 0.8	Vdc	

LVCMOS Output Characteristics

Parameter		Minimum	Nominal	Maximum	Units	Notes
Load		-	-	15	pF	
Voltage	High (Voh)	2.97	-	-	Vdc	
	Low (Vol)	-	-	0.33		
Current	High (Ioh)	-8	-	-	mA	
	Low (Iol)	-	-	8		
Duty Cycle at 50% of Vcc		40	50	60	%	
Rise / Fall Time 10% to 80%		-	2	6	ns	
Start-Up Time		-	-	10	ms	
Period Jitter		-	3	5	ps RMS	
Integrated Phase Jitter (BW=12KHz to 20MHz)		-	0.3	1.0		

- Uiteindelijke schema: 66 MHz clock voor ADC
- J5 UFL als clockinput mogelijk met AEXT low



- Conclusie:
  Hardware kandidaten voor eigen implementatie GPS-DO

- KiwiSDR → Chips en boards (voorlopig) leverbaar

- Piksi (discontinued, wel dual-frequency opvolgers, maxim chip en onderdelen leverbaar)

  - TCXO defineert afwijking in 66 MHz clock rel. tov. GPS (of E1 Galileo via SW), reeds zichtbaar in KiwiSDR user-interface
  - Galileo satellieten zichtbaar in KiwiSDR, maar niet meegenomen in PVT solution

  Voorstel experiment:
  - externe (10 MHz) OCXO samplen met 66 MHz clock, 30 MHz low-pass filter, track cycle drift
  - OCXO heater / tempco aansturen met een (precison) DAC en power stage

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GPS TCXO → long term stability clock source

66 MHz ADC clock → OCXO digitisation clock / HF receiver

External OCXO / Rubidium → short term stability clock to be disciplined / verified