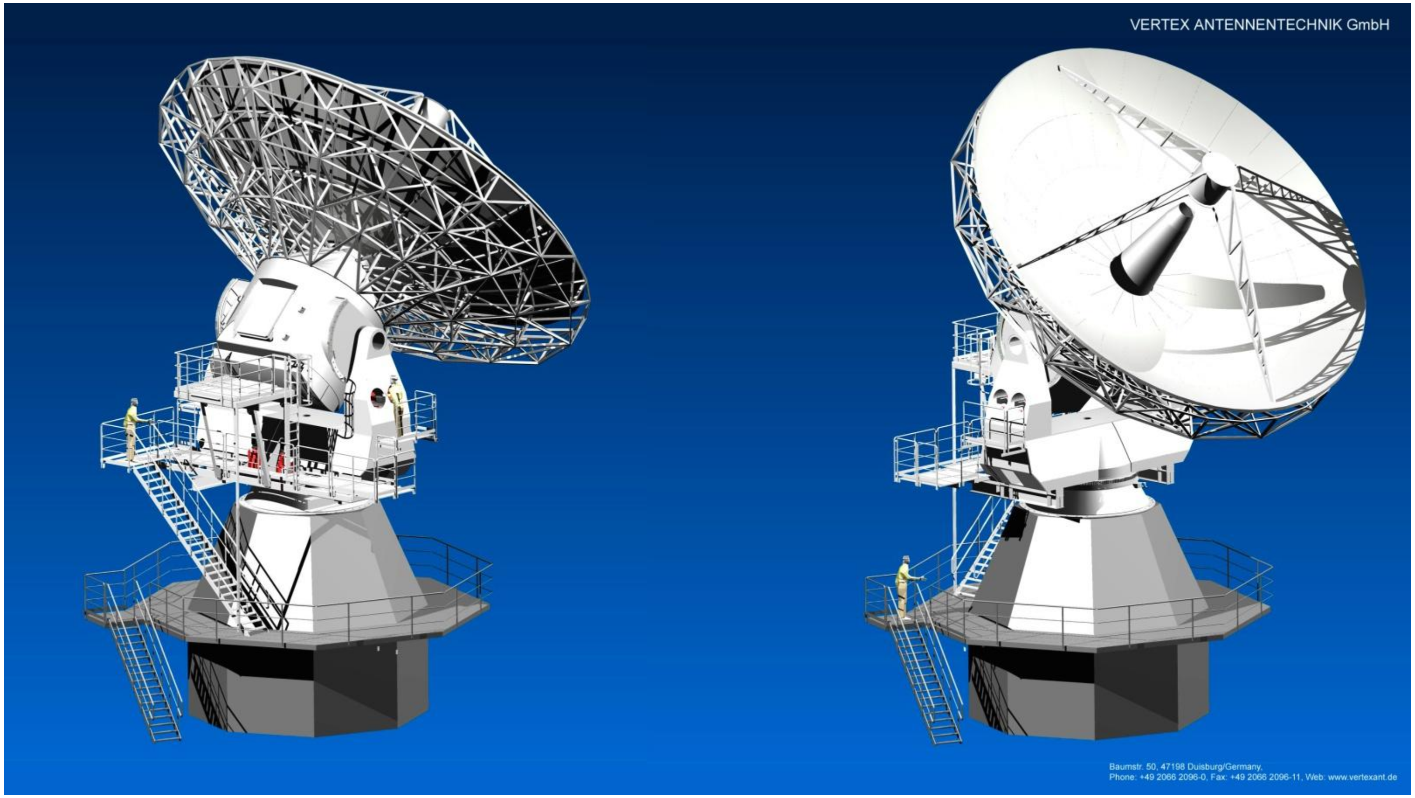
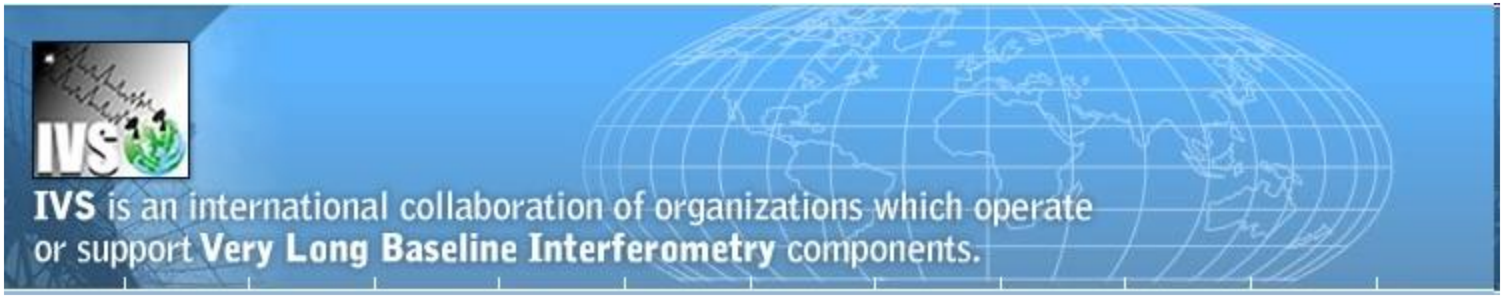
VLBI 2010

Critical Design Points



G. Kronschnabl, A. Neidhardt, K. Pausch, W. Göldi, T. Ekebrand, B. Corey, B. Petrachenko, Jan Kodet, Ch. Plötz;

VLBI 2010



IVS is an international collaboration of organizations which operate or support **Very Long Baseline Interferometry** components.

IVS WG 3 – VLBI2010: Current and future requirements for geodetic VLBI Systems

Goals for a next generation VLBI-System:

- Determination of the relative position better than 1 mm / year
- Continuous observation of the Earth Orientation Parameters
- Very fast generation and distribution of the IVS-Products

➔ continuous, improved UT1 monitoring
➔ Improving of the Celestial Reference Frame (CRF)

Source: IVS WG3 Final Report - ftp://ivscc.gsfc.nasa.gov/pub/annual-reports/2005/pdf/spcl-vlbi2010.pdf

How to do that?

- Increasing the numbers of radio sources (up to 1000 scans/day!)
- Improvement of the Delay Observable
- Reduction von systematic errors, i.e. at the electronic devices, the antenna deformation and of the source structures
- Continuous observation rows the whole year (2 antennas)
- Improving of the network geometry
- New improved strategies at the data analysis
- Improved observation schedules
- Additional measurement system, such as a WVR
- Online data transfer via Internet
- Software correlation
- Remote observations

VLBI 2010 requirements

VLBI 2010

What are the requirements for a new observation system to fulfill the VLBI 2010 specifications?

- A fast moving antenna system with an antenna diameter of 12m or more
- A broadband receiving system at least from 2 to 14 GHz, optional a receiver at S-, X-, and Ka-Band
  - ➔ S- und X-Band compatibility (RCP)
  - ➔ stable phase centre and stable reference point
  - ➔ high antenna efficiency and low system temperature
- Improved reference and calibration systems
- New digital data acquisition systems

What does it mean, to

- **increase the number of observations means:**
  - Reducing the observation time (i. e. the Integration time) needs a
  - ➔ better SNR ➔ (< Tsys; > higher effective Antenna area)
  - ➔ higher bandwidth (New feeds, new receivers; data boosters)
  - Reducing the slewing time needs
  - ➔ faster antenna drives
  - ➔ more energy consumption
  - ➔ a better mechanical construction
  - ➔ more attrition and therefore more maintenance
- **reduce systematic errors, such as at the electronic devices, the antenna deformation and additional calibration systems:**
  - ➔ better time and frequency reference
  - ➔ improving of the phase delay errors, for instance at the cables
  - ➔ new improved calibration systems
  - ➔ additional measurement systems ➔ Water Vapor Radiometer ?

What are the key points for such an Antenna?

- Antenna diameter size 12m or more
- Fast moving antennas
- Broadband or multiband capability
- Extreme stiff reflector
- High efficiency reflector
- Low path length error
- Very good and stable reference point
- Very stabile towers
- Phase stable cables and cable wraps
- Stabile phase centre of the feed (almost frequency independent)
- Remote control
- Energy saving techniques
- Improved time and frequency reference system

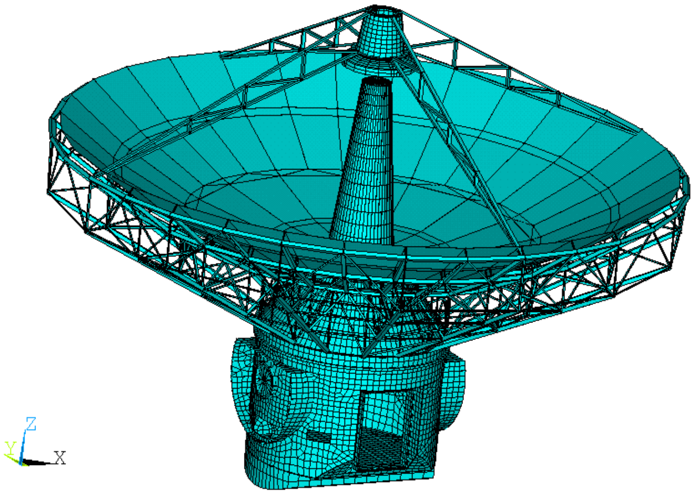
How did we realized that at Wettzell?

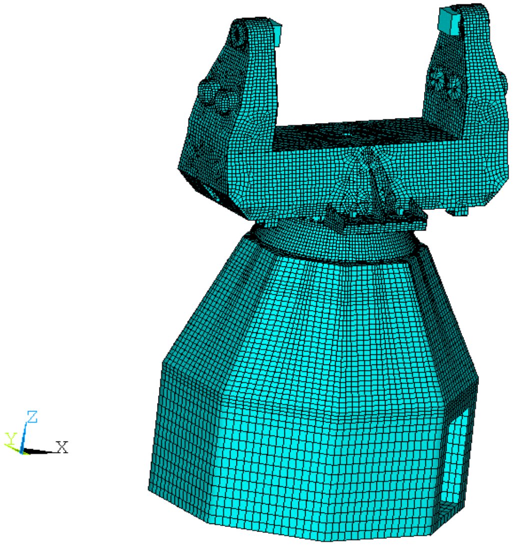
Microwave Antenna design:

- Excellent antenna efficiency by the Ringfocal Design a flare angle of about 65
- No blockage by the Subreflector
- Broadband capability > 40 GHz
- Low ground pickup noise
- Mechanical correction of the Subreflector

Mechanical Antenne design:

- Very low Path Length Error
- Extreme stiff Main- and Subreflector,
- Extreme stiff Elevation cabin and Azimuth yoke
- Excellent Azimuth- and Elevation bearings
- High resolution hollow shaft encoder
- Very stable towers with a big basement
- Vertical and horizontal axis offset less than 5 arcsec
- Balanced antenna design with counterweights

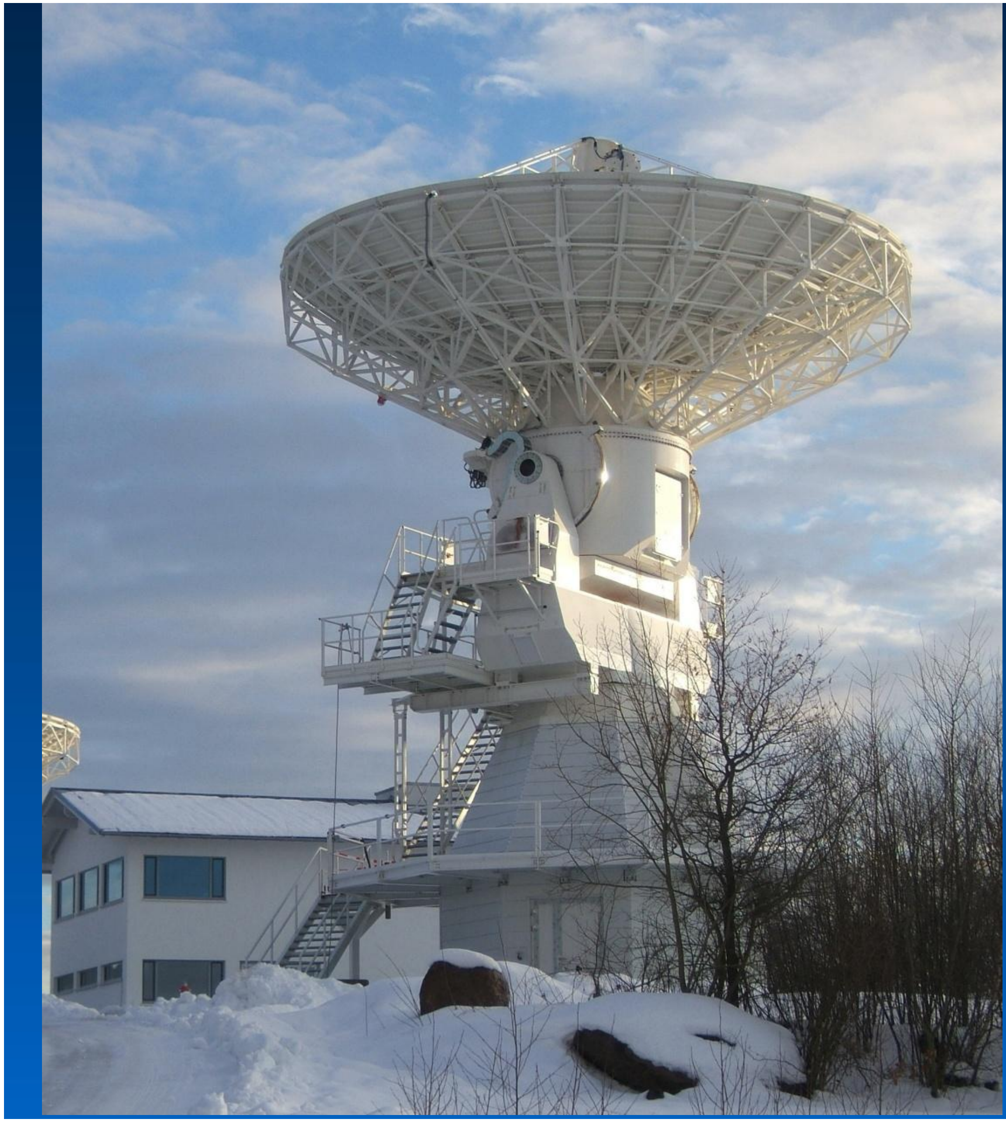




TWIN - Radioteleskop

Technical Data:

- Main reflector: 13.2m
- Ringfocal-Design
- f/D = 0.29
- Path Length Error <0.3mm
- ALMA Mounting with drive velocities of 12 /s in Azimuth and 6 /s in Elevation
- Drive range +/- 270 & 115
- Balanced antenna design
- Excellent bearings
- 27Bit Encoder : 0.0003 resolution
- Subreflector adjustable by a Hexapod



TWIN – Radioteleskop: Path Length Error

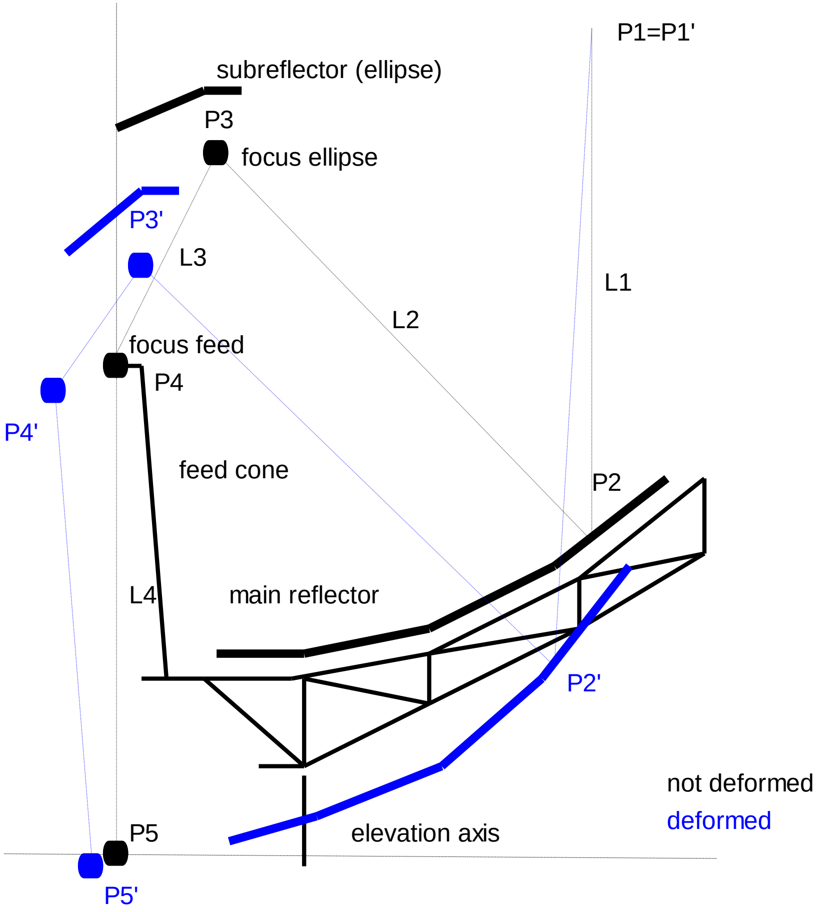
The TTW-Antenna is designed for a Path Length Error of less than 0.3mm !!

L1 = distance main axis – reflector surface
L2 = distance reflector surface – subreflector
L3 = distance subreflektor – feed focus
L4 = distance feed focus – axis intersection point

Definition: Path Length Error

- Lnot_deformed = L1+L2+L3+L4
- Ldeformed = (L1+dL1)+(L2+dL2)+(L3+dL3)+(L4+dL4)
- L_Error = Ldeformed - Lnot_deformed

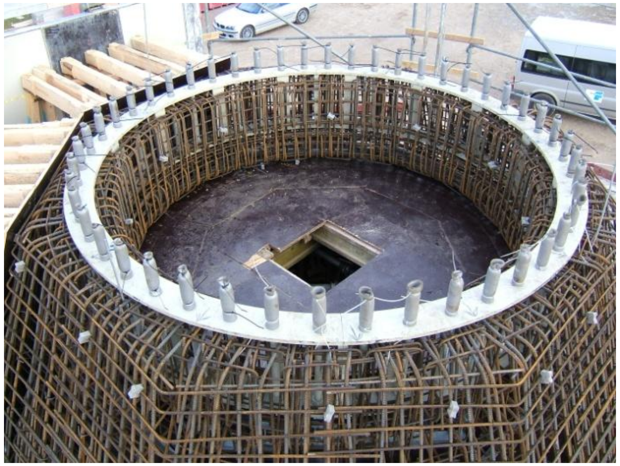
$$PathLengthError = \frac{\sum_{i=1}^{192} \left(A_i \cdot PathLengthError_i\right)}{\sum_{i=1}^{192} A_i}$$



Source: Vertex Design Review; Dez. 2008

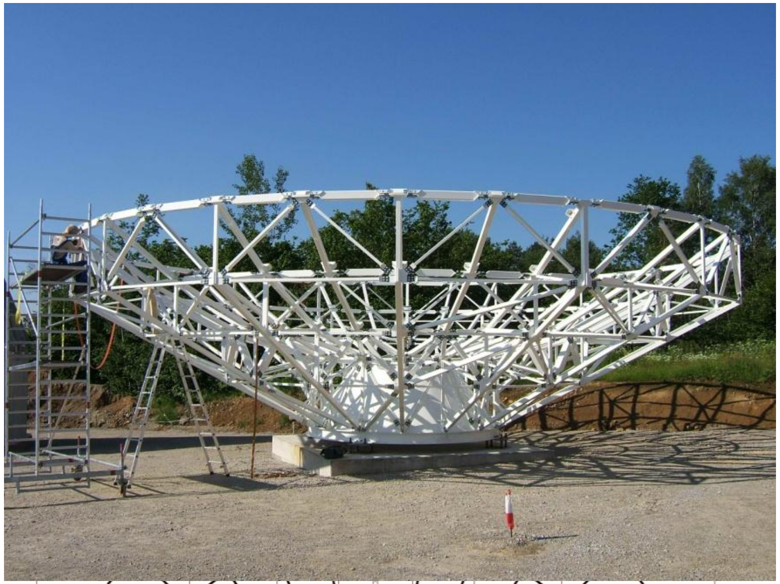
Towers for TTW

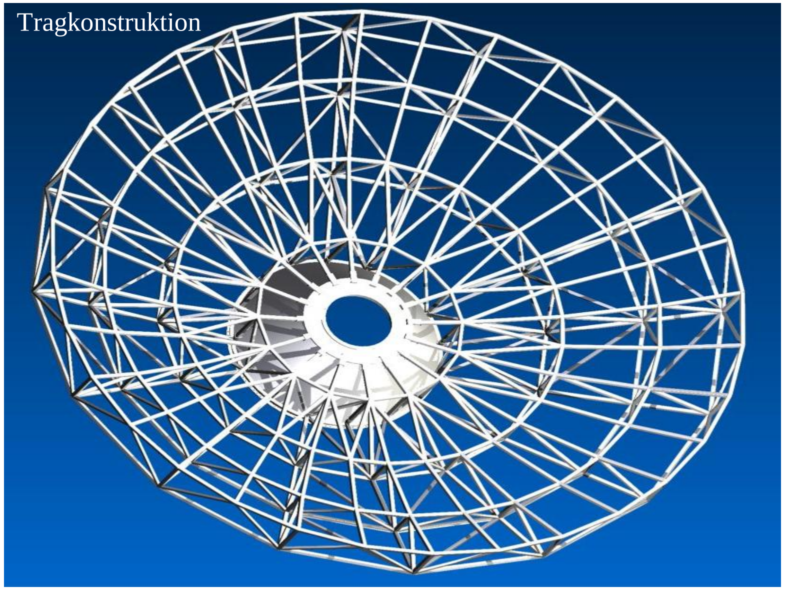
- Basement up to 6m in the ground
- Thick concret walls containing tons of steel

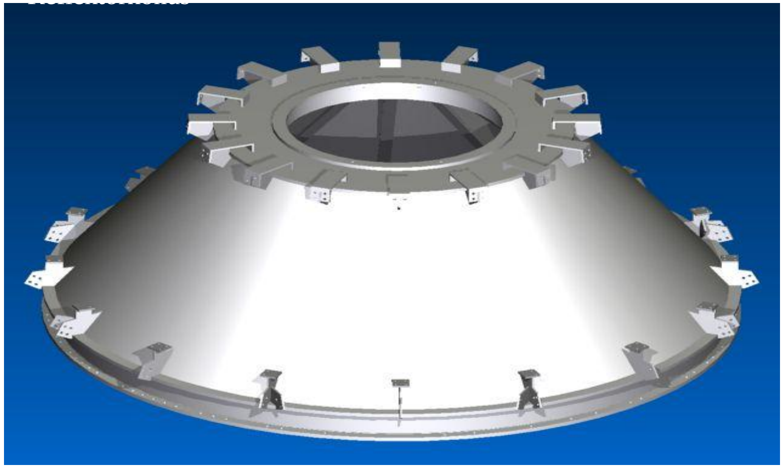


Zul. $\varphi_{OKT} \leq 0{,}0005\,°$	Unter Wind ≤ 40 km/h, Böen bis 50 km/h
Zul. $\varphi_{OKT} \leq 0{,}0015\,°$	Unter Temperatureinwirkung

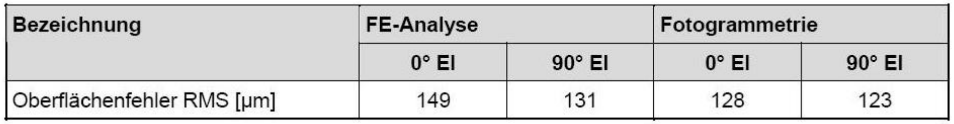
TWIN – Radiotelescope: Main reflector construction





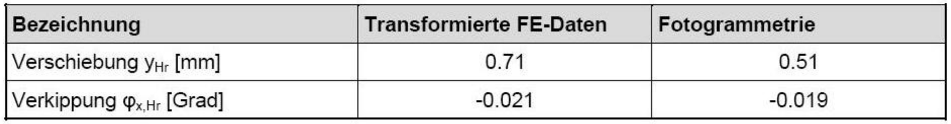


Reference planes of TTW



Bezeichnung	FE-Analyse		Fotogrammetrie	
	0° El	90° El	0° El	90° El
Oberflächenfehler RMS [µm]	149	131	128	123

Tab. 2-13: Oberflächenfehler des Hauptreflektors



Bezeichnung	Transformierte FE-Daten	Fotogrammetrie
Verschiebung y_{Hr} [mm]	0.71	0.51
Verkippung $\varphi_{x,Hr}$ [Grad]	-0.021	-0.019

Tab. 2-14: Vergleich von Hauptreflektordaten bei der Elevationsänderung 90°->0°

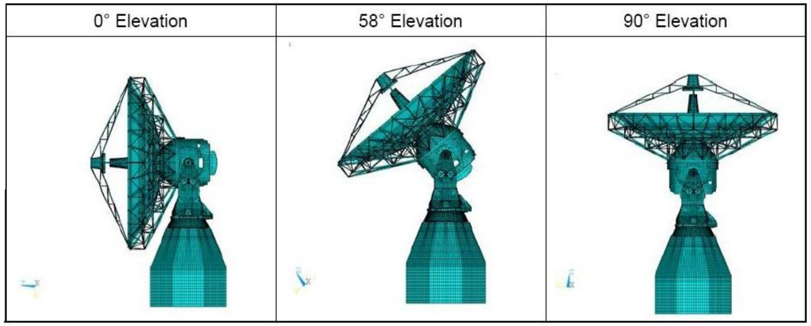
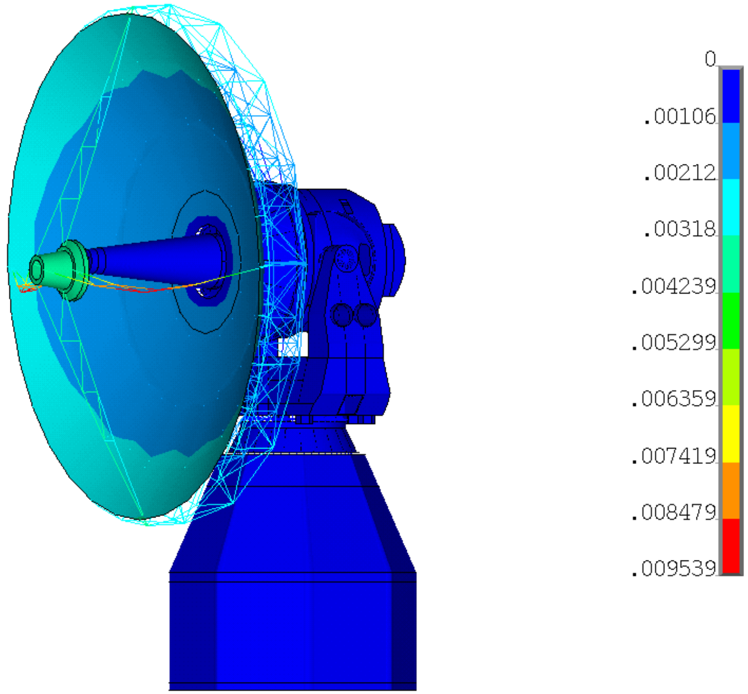
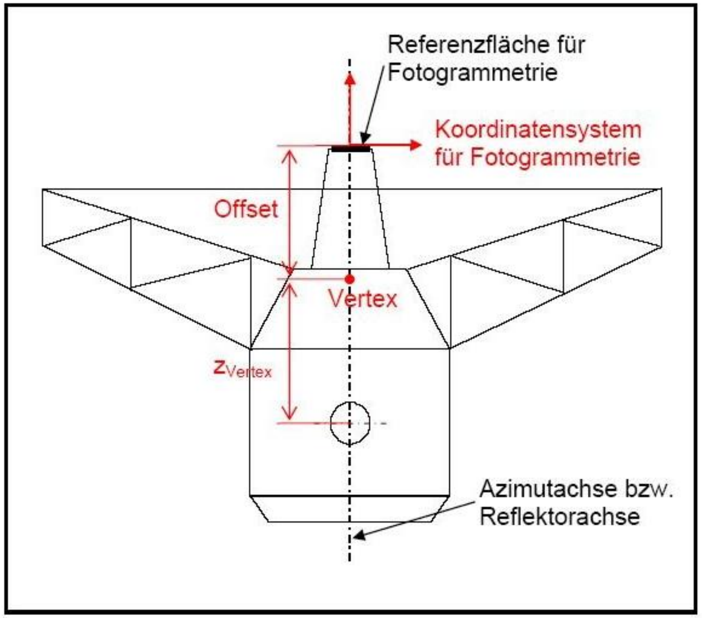


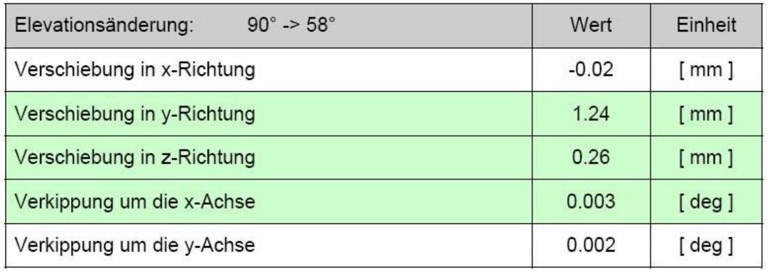
Abb. 2-1: FE-Modelle der TTW-Antenne bei 0 Grad, 58 Grad und 90 Grad Elevation





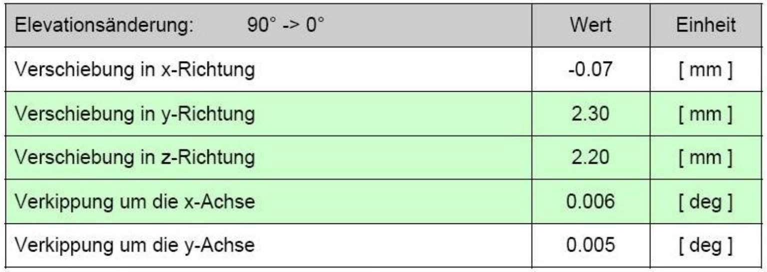
Prinzipskizze zur Referenzfläche für die Fotogrammetrie

Deformation of the Subreflector



Elevationsänderung: 90° -> 58°	Wert	Einheit
Verschiebung in x-Richtung	-0.02	[mm]
Verschiebung in y-Richtung	1.24	[mm]
Verschiebung in z-Richtung	0.26	[mm]
Verkippung um die x-Achse	0.003	[deg]
Verkippung um die y-Achse	0.002	[deg]

Tab. 10-1: Messprotokoll der gemessenen Subreflektorverschiebungen und -verkippungen bei Elevationsänderung von 90° nach 58°



Elevationsänderung: 90° -> 0°	Wert	Einheit
Verschiebung in x-Richtung	-0.07	[mm]
Verschiebung in y-Richtung	2.30	[mm]
Verschiebung in z-Richtung	2.20	[mm]
Verkippung um die x-Achse	0.006	[deg]
Verkippung um die y-Achse	0.005	[deg]

Tab. 10-2: Messprotokoll der gemessenen Subreflektorverschiebungen und -verkippungen bei Elevationsänderung von 90° nach 0°

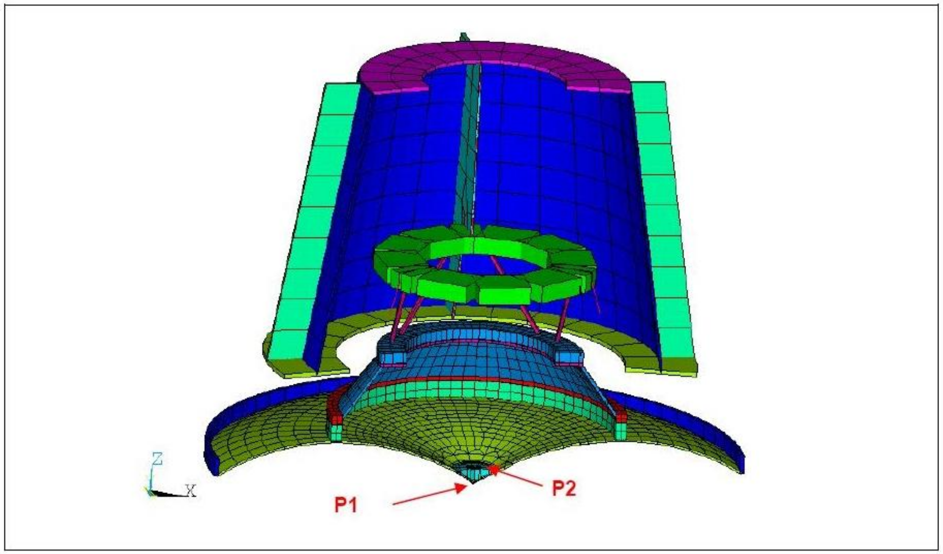
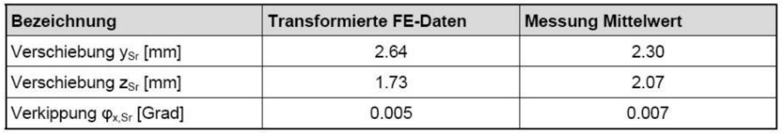


Abb. 2-3: Kopfteil mit Subreflektor und Auswertepunkte P1 und P2



Bezeichnung	Transformierte FE-Daten	Messung Mittelwert
Verschiebung y_{Sr} [mm]	2.64	2.30
Verschiebung z_{Sr} [mm]	1.73	2.07
Verkippung $\varphi_{x,Sr}$ [Grad]	0.005	0.007

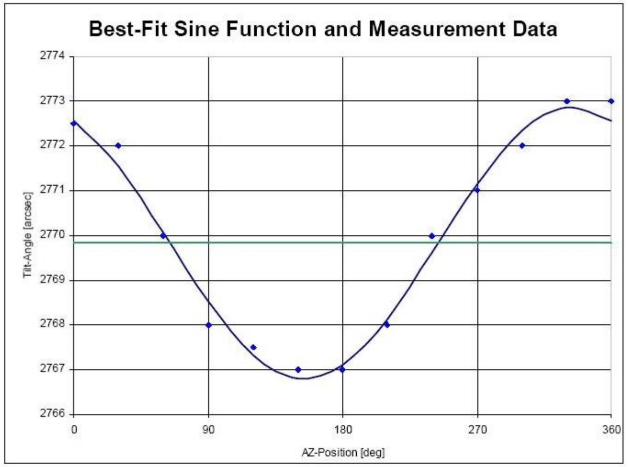
Tab. 2-15: Vergleich von Subreflektordaten bei der Elevationsänderung 90°->0°

LF1 = Loading at 58 without Subreflectorcontroller
LF2 = Loading at 58 with Subreflectorcontoller
LF3 = Load with wind speed 40km/h ahead
LF4 = Load with wind from one side

LF	Gain 33 GHz [dBi]	Δ-Gain [dB]	η	RMS σ [mm]
nominell	72.412			
1	72.193	-0.219	0.951	0.16
2	72.318	-0.094	0.979	0.11
3	72.408	-0.004	0.999	0.02
4	72.409	-0.003	0.999	0.02

Tab. 3-1: Betrachtung des Antennengewinns

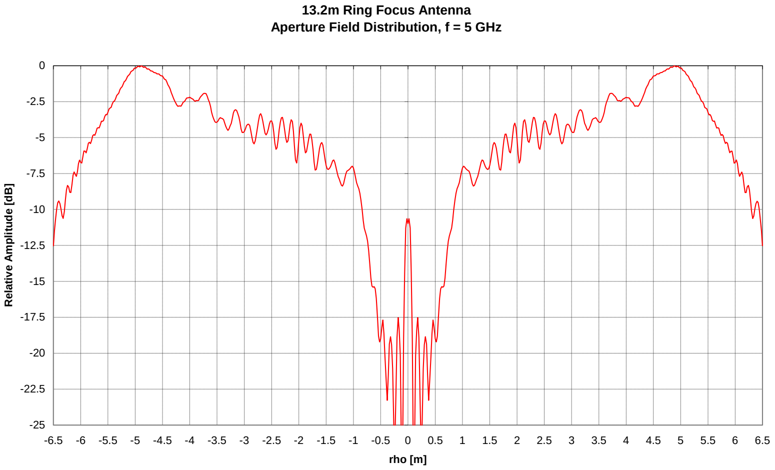
Measurements of the vertical and horizontal axis and the intersection point



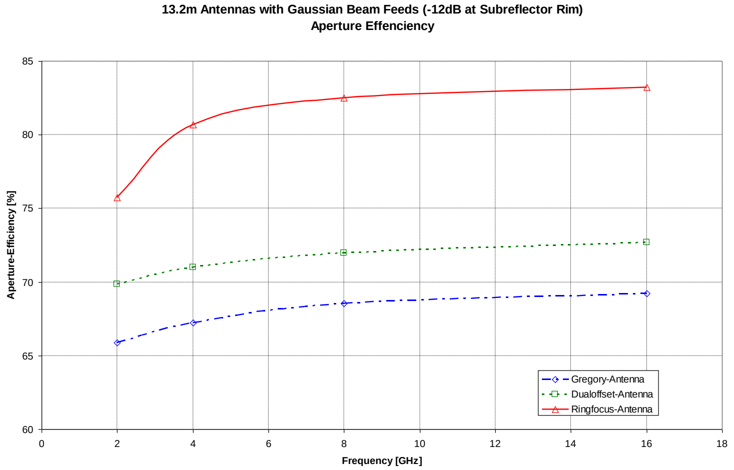
Darstellung von Messwerten der Azimutachsmessung sowie deren Bestfit-Sinusfunktion

TWIN Radioteleskop: Main reflector

Distribution of the radiated energy

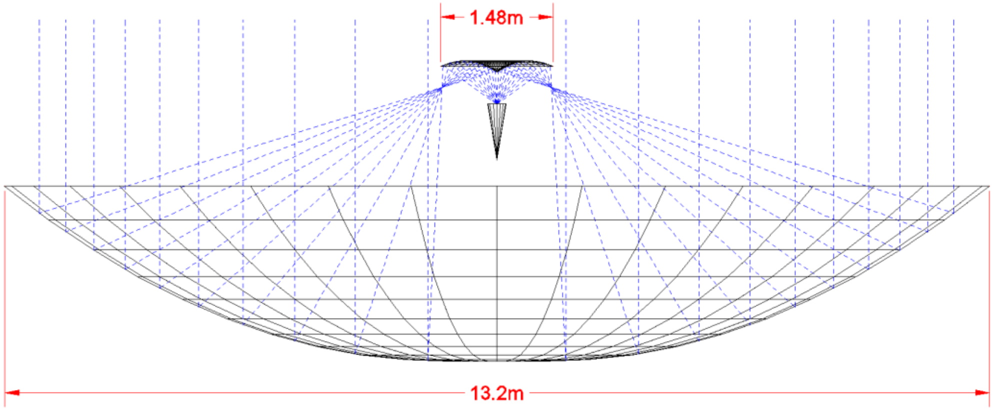


Effective beam efficiency



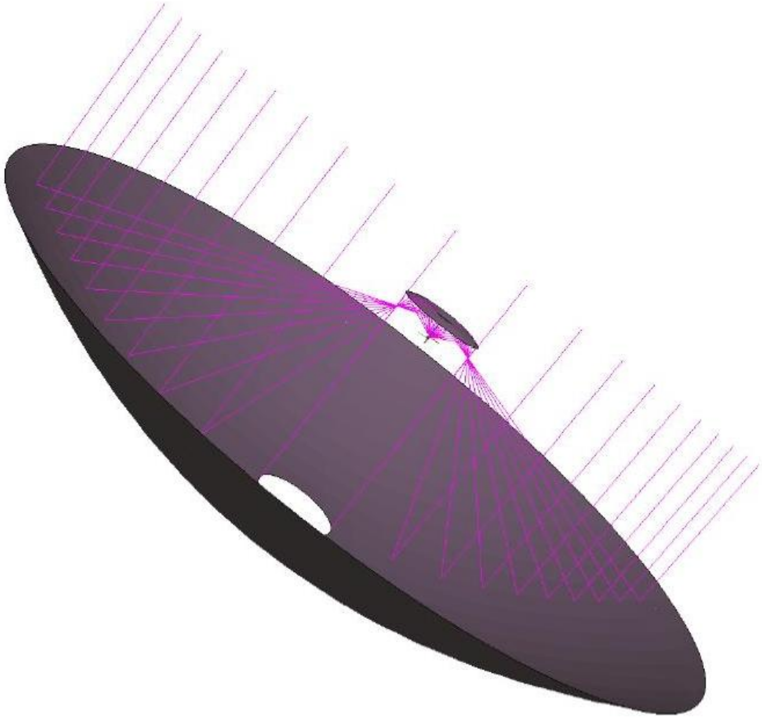
Ringfocal-Design

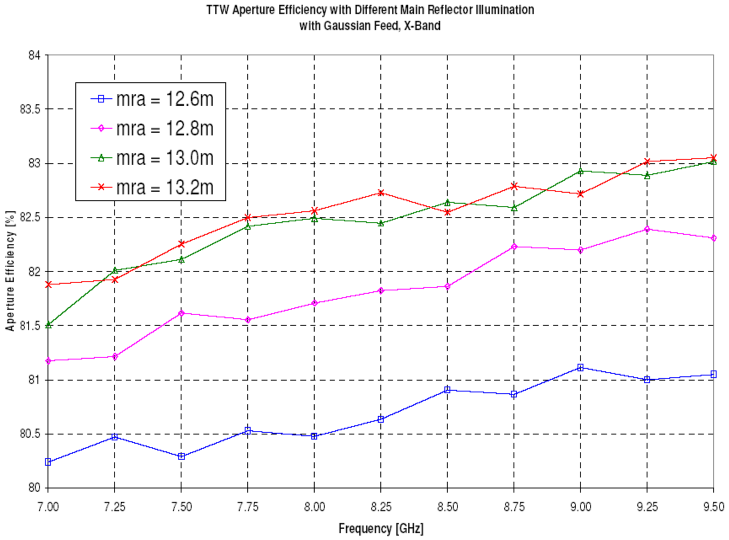
- Dual-Reflector receiving system
- optimal for large flare angles
- no blockage by the subreflector
- high illumination efficiency
- the feed horn is prevented by radiation from the sun

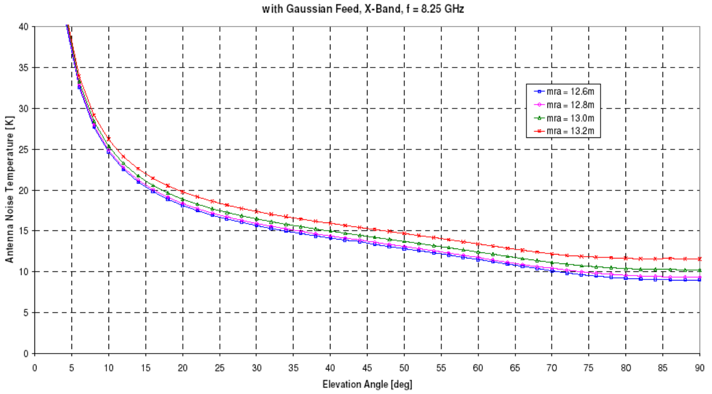


Source: Willi Göldi, Mirad; FRFF-Workshop 2009, Wettzell

Antenna efficiency and ground noise pickup

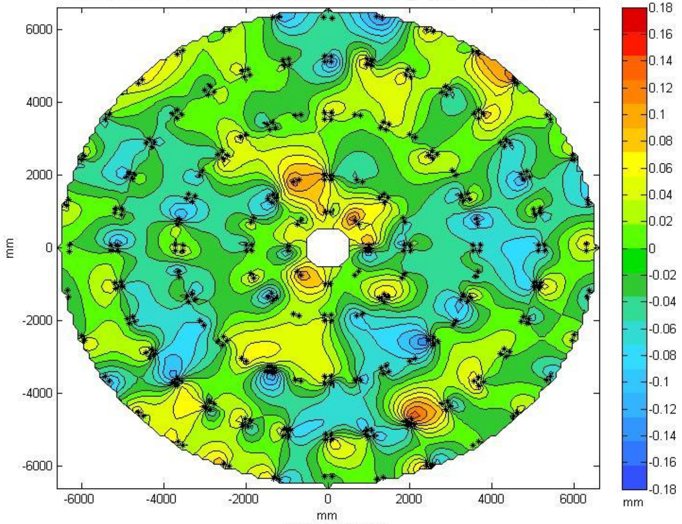






Photogrammetry

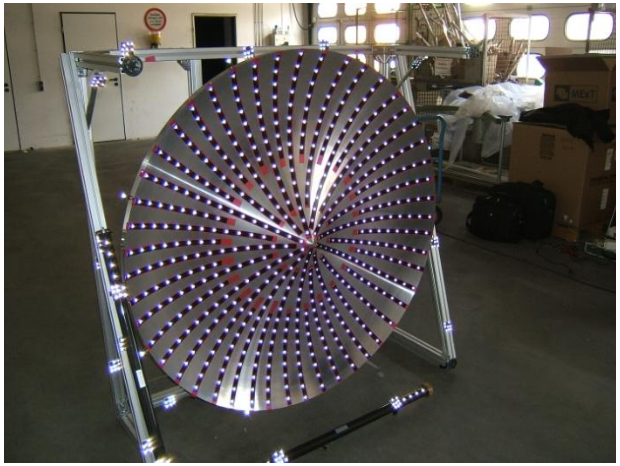
Main reflector



Antenne #1: Abschlussmessung (58° Elevation)

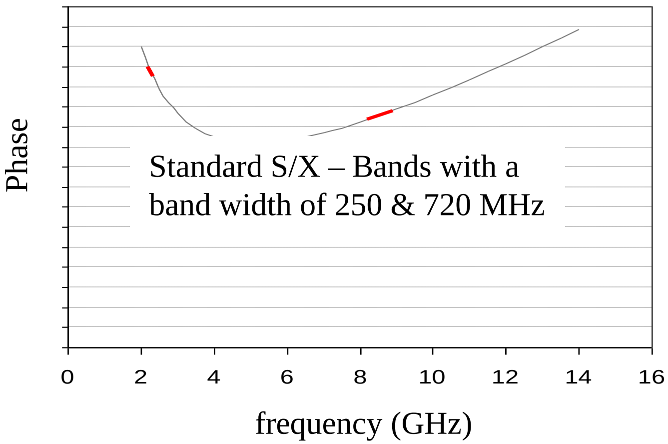
rms = 53 µm

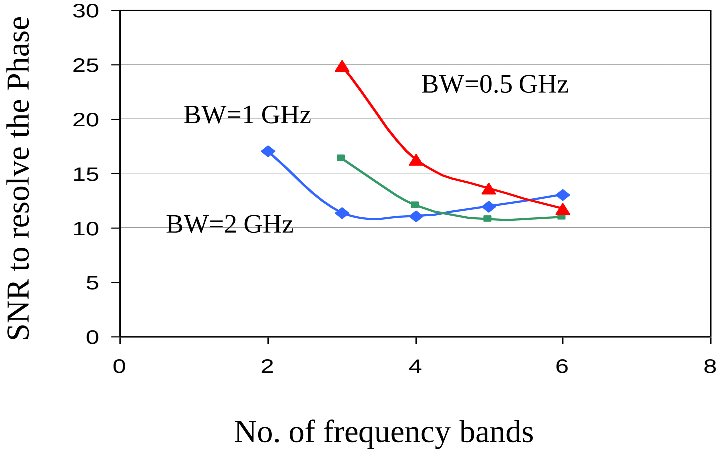
FAT Subreflector

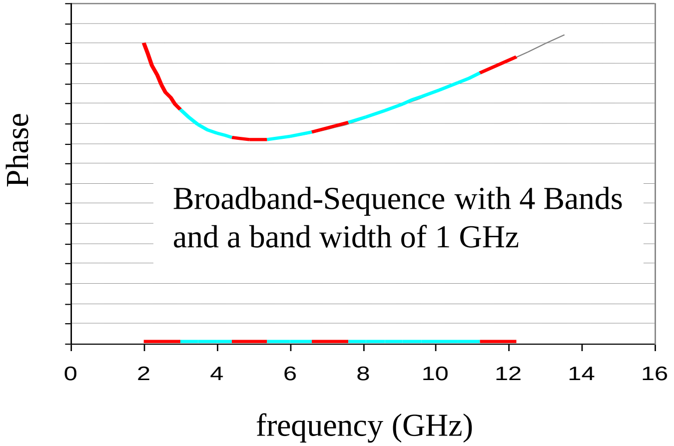


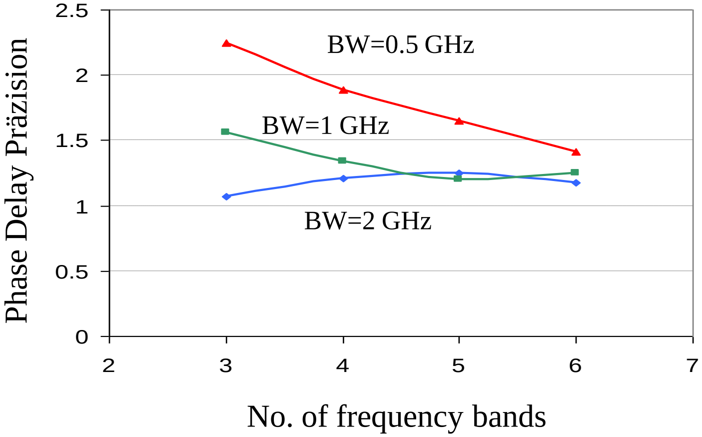
VLBI 2010: Broadband Delay

Delay precision target:	4-ps (in reality larger)
Frequency range:	2-18 GHz; (in reality 14 GHz with reasonable efficiency)
Number of bands:	4
Bandwidth per band:	1 GHz


Standard S/X – Bands with a band width of 250 & 720 MHz



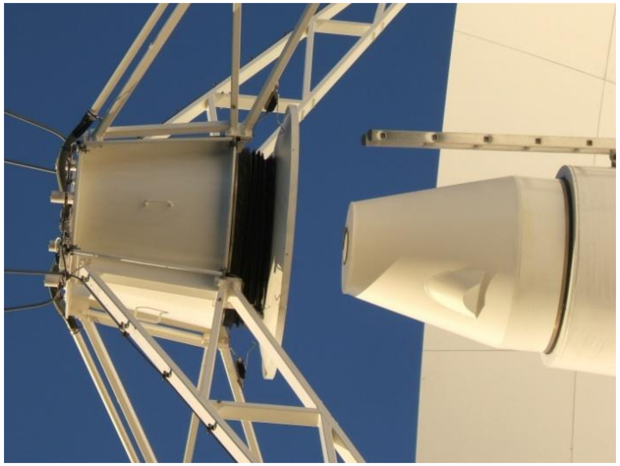

Broadband-Sequence with 4 Bands and a band width of 1 GHz



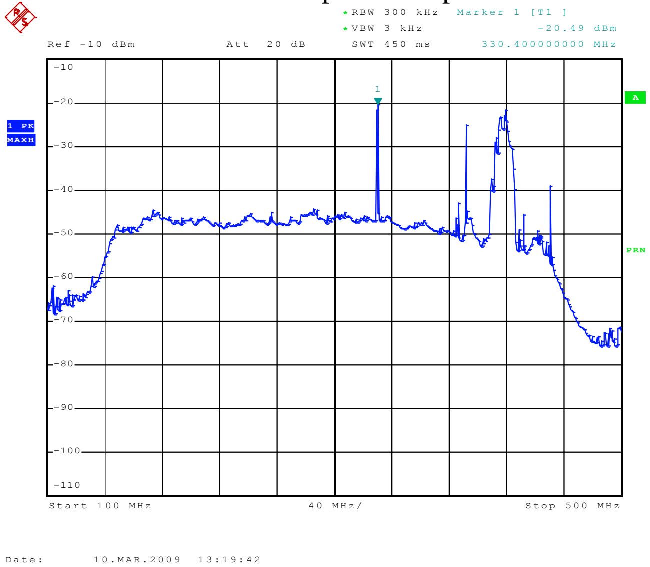
Source: B. Petrachenko: Broadband Delay Tutorial, FRFF Wettzell 2009

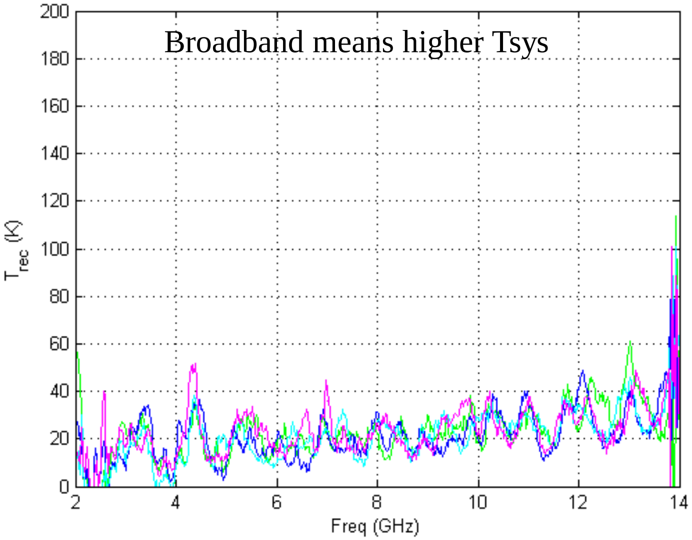
Wideband Disadvateges?

Subreflector is very close to the feed



RFI could be a potential problem

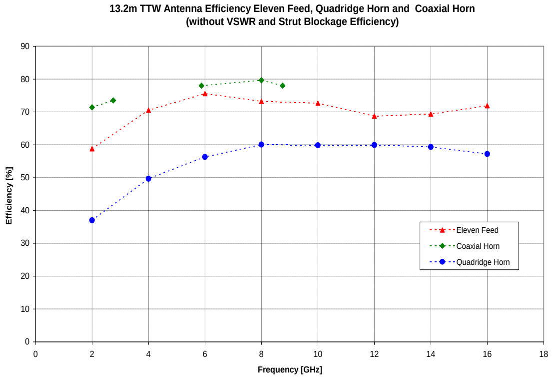




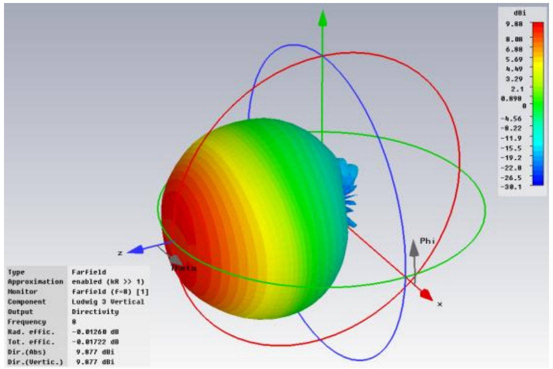
- Huge amount of data
- Data handling and storage
- Correlation time increases

Broadband-Receivingsystem: Feedhorn

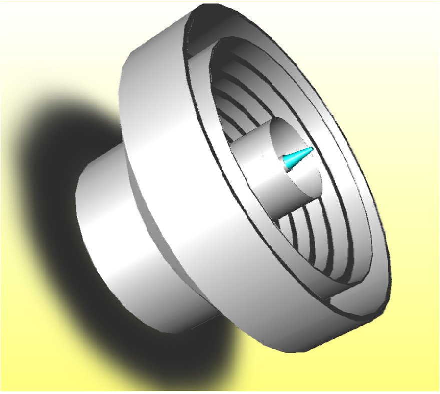
A broadband feed has a wide flare angle! (65)



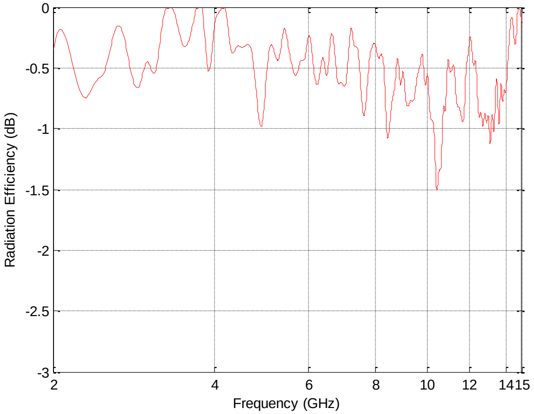
Triband Coaxial-Feed

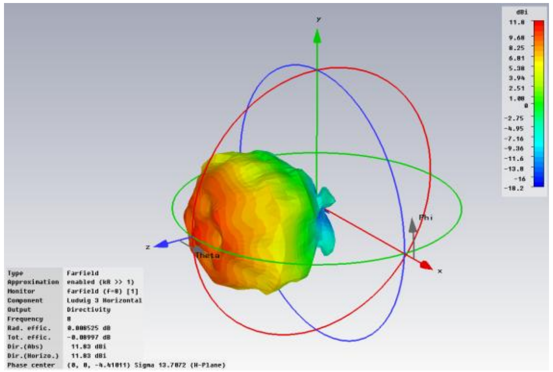


Type Farfield
Approximation enabled (kR >> 1)
Monitor farfield (f=8) [1]
Component Ludwig 3 Vertical
Output Directivity
Frequency 8
Rad. effic. -0.01260 dB
Tot. effic. -0.01722 dB
Dir.(Abs) 9.877 dBi
Dir.(Vertic.) 9.877 dBi

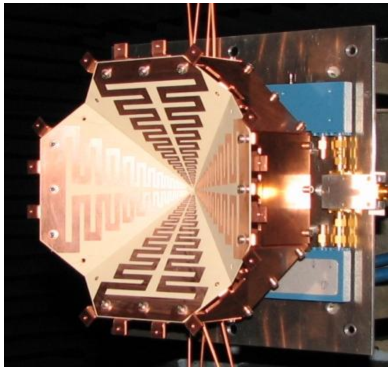


Eleven Feed



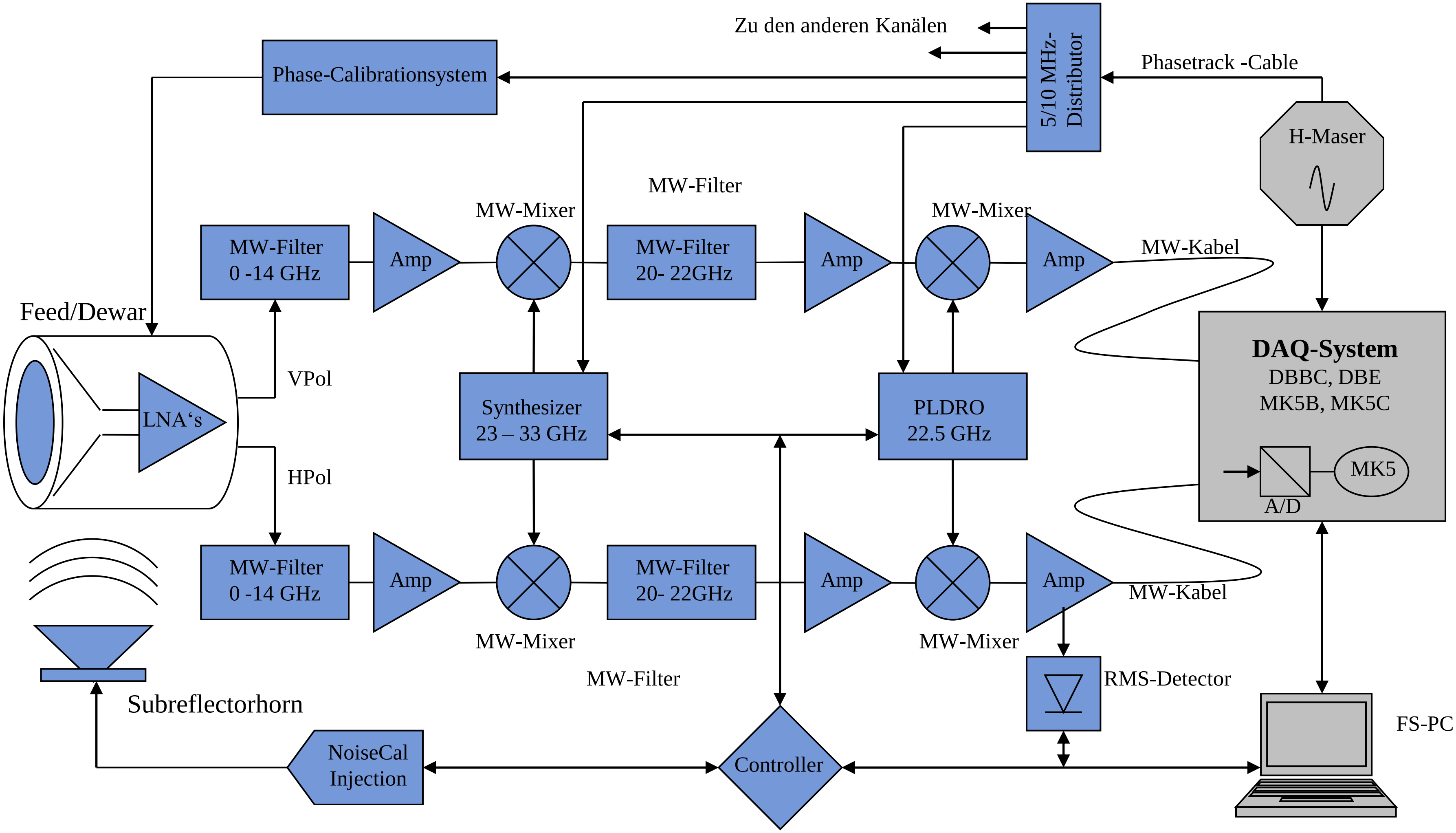


Type Farfield
Approximation enabled (kR >> 1)
Monitor farfield (f=8) [1]
Component Ludwig 3 Horizontal
Output Directivity
Frequency 8
Rad. effic. 0.008525 dB
Tot. effic. -0.08997 dB
Dir.(Abs) 11.83 dBi
Dir.(Horizo.) 11.83 dBi
Phase center (0, 0, -4.41011) Sigma 13.7072 (H-Plane)

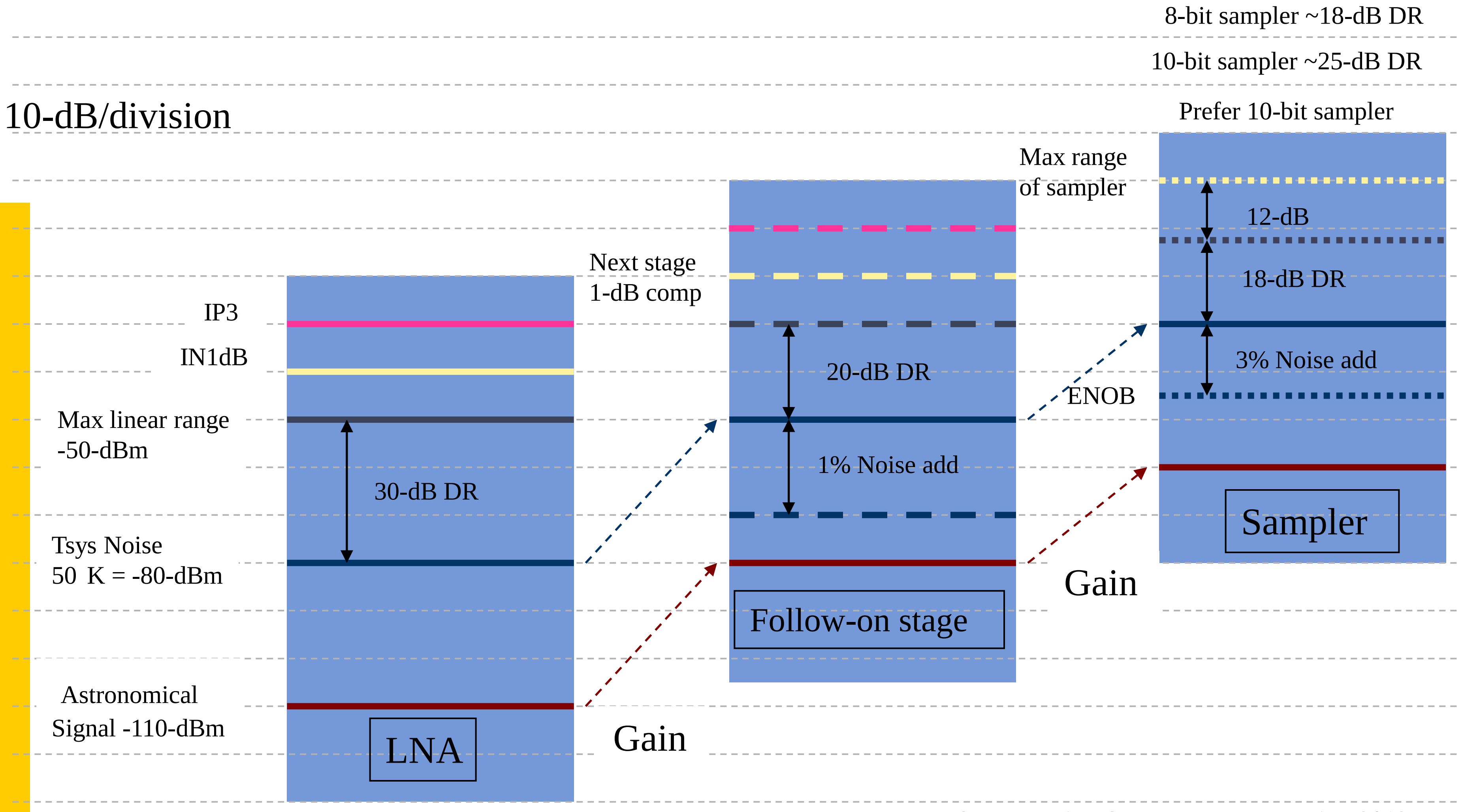


Source: Willi Göldi, Mirad; S. Kildal, Chalmers Univ.; FRFF-Workshop 2009, Wettzell

Receiving-System: Wideband-Receiver

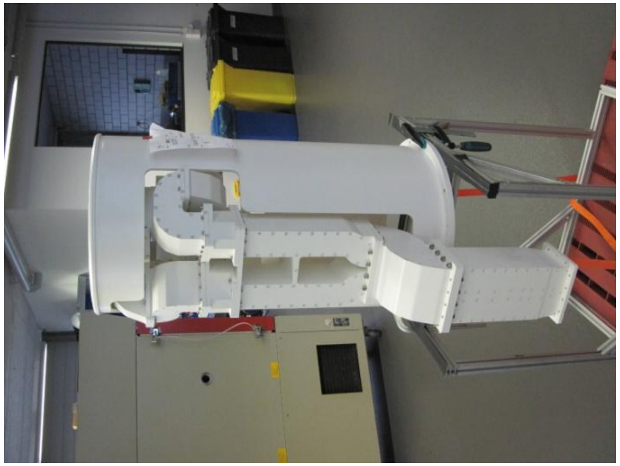


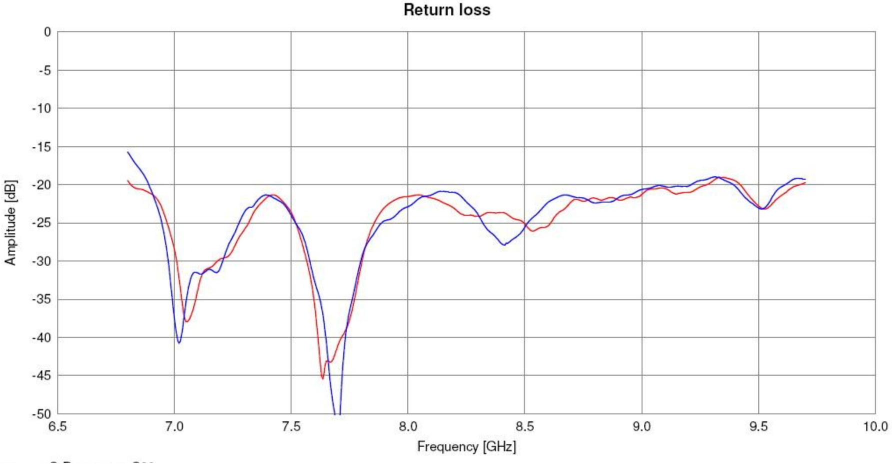
Receiver Dynamic Range

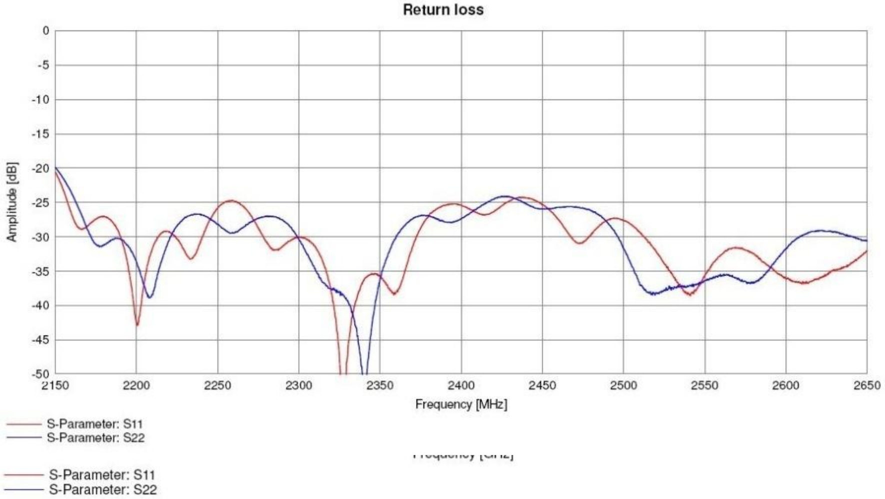


Source: Brian Corey; Tecspec-Meeting 2012

First measurement results of the new Triband-Feed

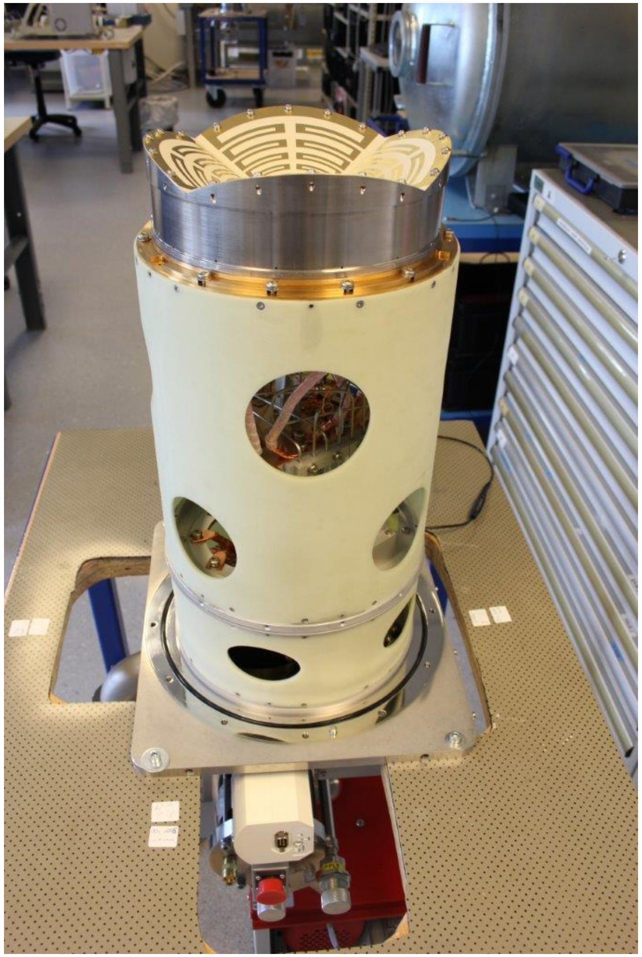




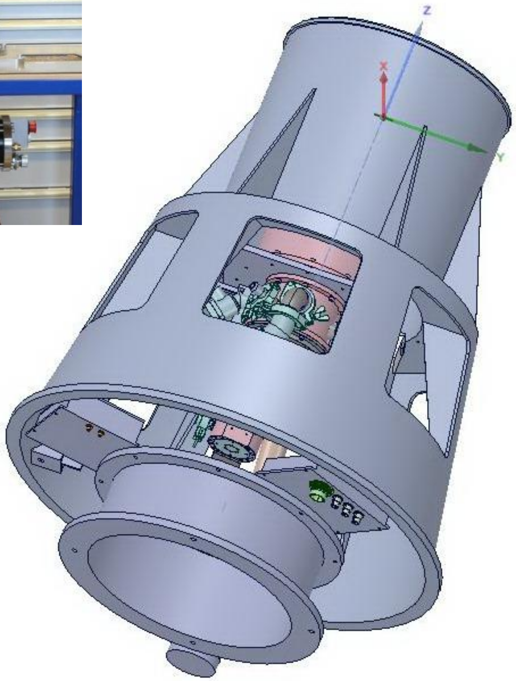


Design Status Elevenfeed

Elevenfeed with Cyrosystem



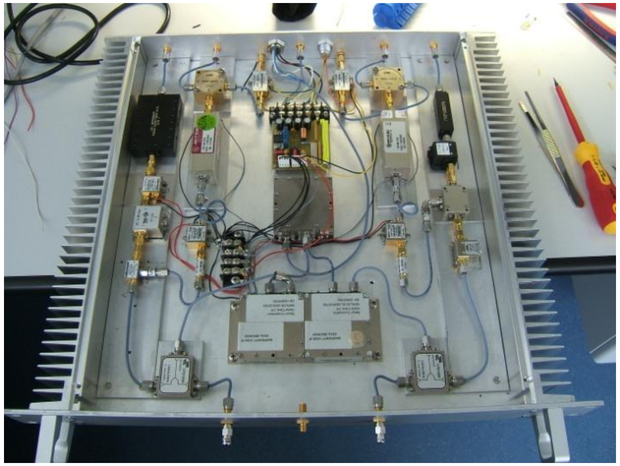
Elevenfeed Dewar



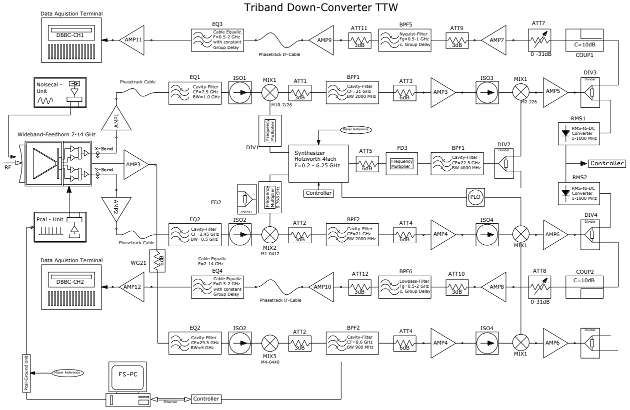
Receiver Cone

TTW1 Receiver Design

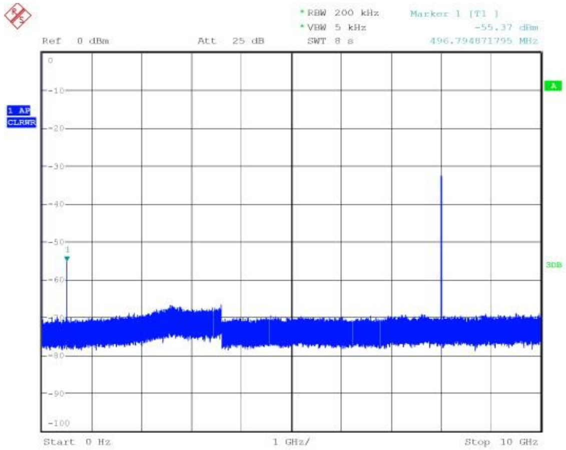
S/X-Receiver



S/X/Ka-Band Receiver



Tri-Band Receiver



S-Band Up/Down-Converter Measurement

Absolute Time in VLBI

VLBI is ***the*** space-geodetic technique for measuring UT1 = Earth rotation angle relative to universe.
Time error impacts UT1 directly and should be: < 0.1 * 500-ns = ~50-ns.

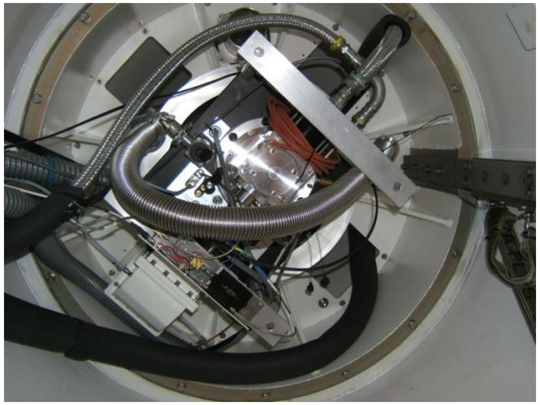
This includes:

Time labelling of sampled data	< ~10-ns
Delay of the PCAL uplink cable	< ~5-ns
Delay of the cable for sampling clock epoch	< ~5-ns
Delay of the GPS cable.	< ~5-ns
Absolute GPS time	< ~50-ns

The UT1 **precision** in VLBI2010 expected to be ~0.5 µs.
To achieve 0.5µs UT1 accuracy, we need to know station time to well under 1 µs relative to UTC.
A value of 50 ns would be good enough, but better accuracy is possible? (source: B. Corey Tecspec-meeting)

100MHz →

Station time reference point !



← 1PPS

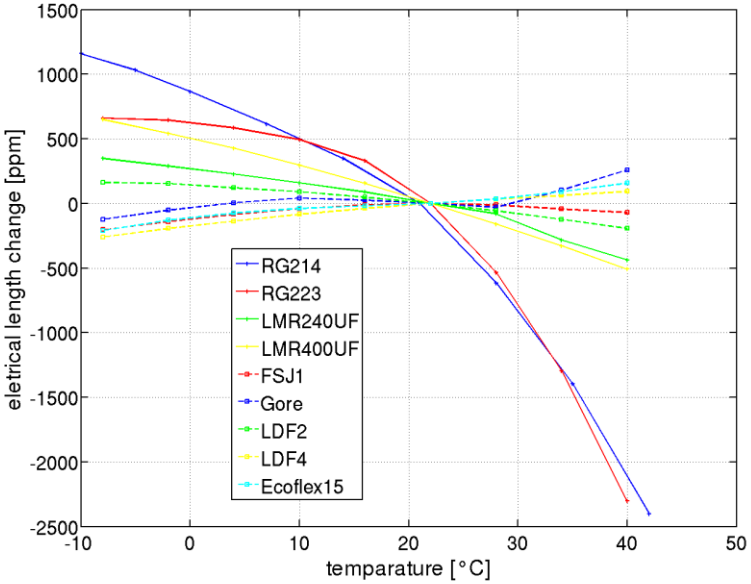
Cable length stability specification

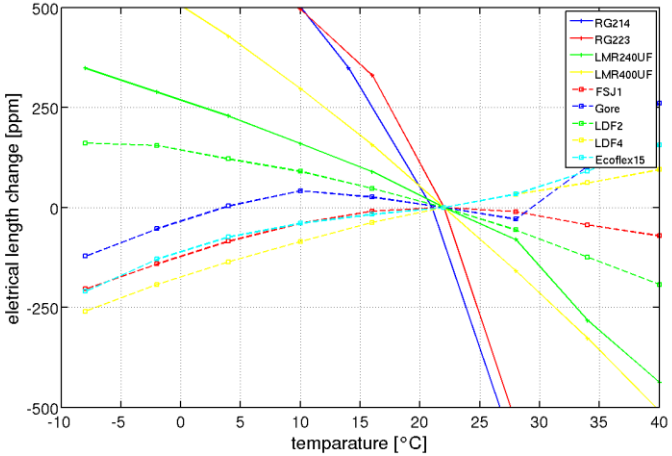
- Cable carrying pcal reference from maser to frontend must be stable in absence of cable cal.
- Specs on pcal reference cable stability in absence of cable measurement system:
  - < 0.3 ps variations that are dependent on antenna orientation
  - Allan std dev < 10^{-15} @ 50 minutes
  - On other time scales, ASD scales with typical maser performance.
- ASD spec also applies to any buffer amp that drives the pcal reference signal.
  - Be sure buffer amp is not sitting in front of air conditioning vent!
- If pcal is absent, effect of variations in sampler clock delay is scaled down by frequency ratio at sampler input and at RF.
- General good practice and possibility of pcal failure argue for using cable with low temperature coefficient for all long cable runs carrying frequency reference.
- Orientation-dependent length variations of pcal ref cable must be < 0.3 ps in absence of cable measurement system.

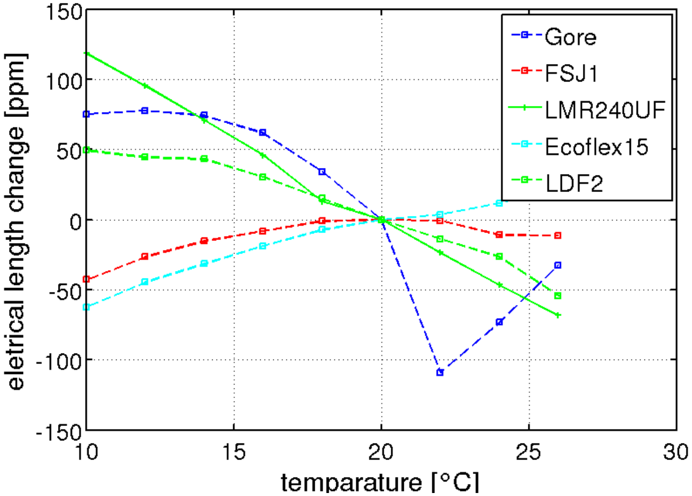
<0.5 ps	LMR-240 coax	1 turn with 10-cm radius
<0.5 ps	LMR-400 Ultraflex coax	1 turn with 8-cm radius
<0.5 ps	Single-mode fiber in “loose bundle”	1 turn with 8-cm radius

Source: Brian Corey; Tecspec-Meeting 2012

Tests of various cables in the temperature camber

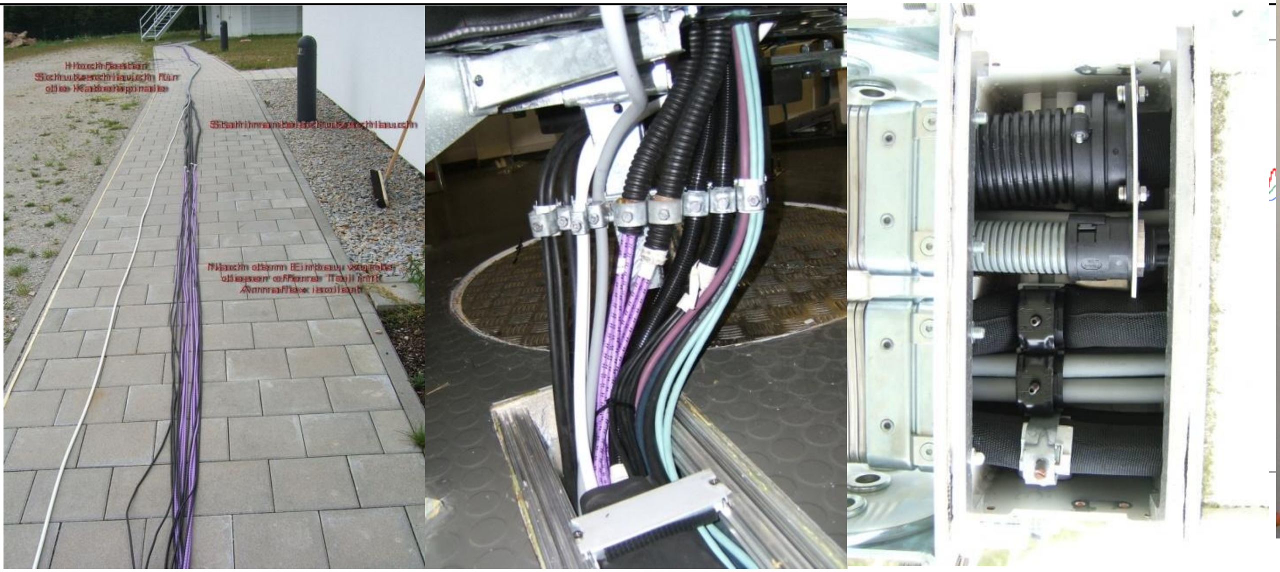






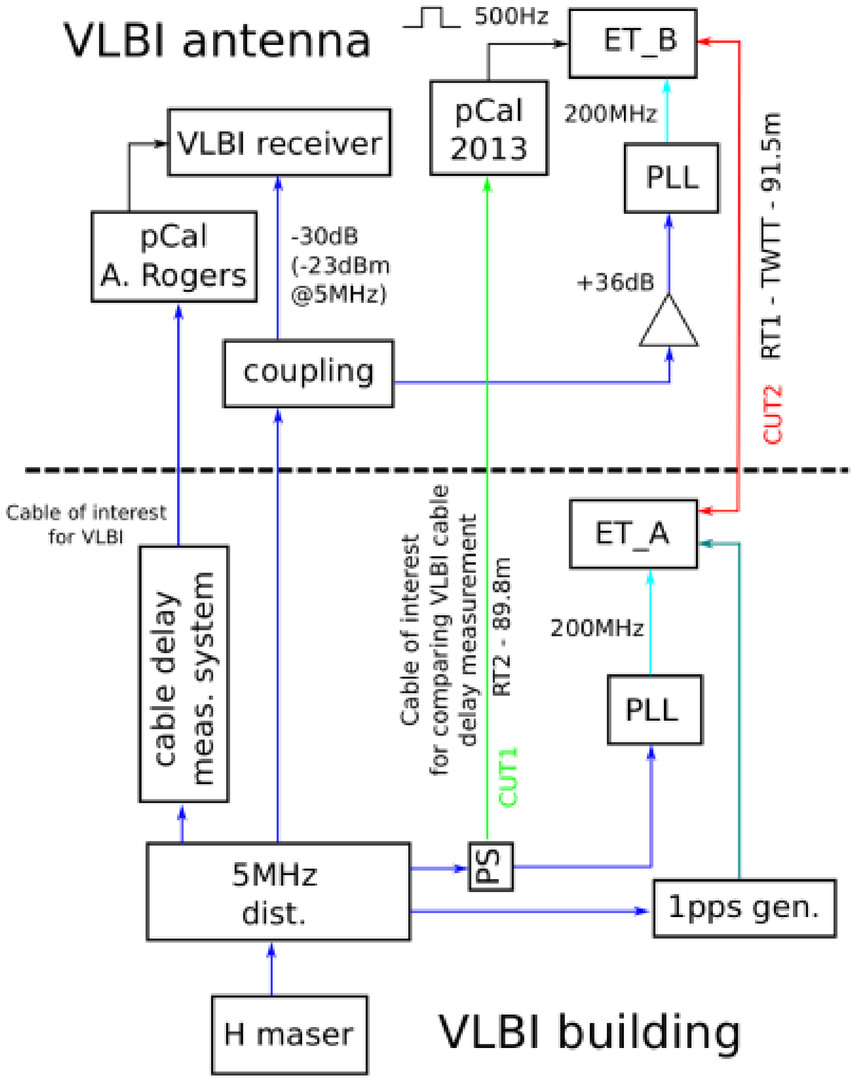
Minimizing temperature-driven cable length variations

- Use cable with low temperature coefficient.
  - Example:
    - 80-m LMR-400 @ 5 MHz: 80m × 4ns/m × 3ppm/K = 1.0 ps/K (upper limit) (AEER)
    - 20-m LMR-400UF @ 5 MHz (cable wrap): 20m × 4ns/m × 9ppm/K = 0.7 ps/K (AEER)
    - 75-m FSJ1 cable @100 MHz : 75m x 4ns/m x 5ppm/K = 1.5 ps/K (J. K
    - 32-m LMR-240UF @ 100 MHz (cable wrap): ~ 1.5 ps/K (J. Kodet)
- Add thermal insulation around exposed cables to increase thermal time
  - Thermal time constant of bare LMR-400 is ~30 minutes.
- Bury cables from control room to antenna pedestal.



New Cable cal system?

- New concept for cable cal
- Based on an Event timer



Phase calibration system

- Primary function: Measure time variations of instrumental phase vs. frequency.
- Secondary functions:
  - Infer T_{sys} variations from phase cal amplitude.
  - Phase/gain equalization for circular polarization generation from linear pol.
- Phase differences between channels will be far more stable in VLBI2010 than in S/X VLBI, thanks to digital IF-to-baseband conversion in FPGAs.
- But phase cal is still needed in VLBI2010 to measure
  - LO phase drifts between bands
  - Phase/delay drifts in RF/IF analog electronicsAs RF bandwidth increases, pulse intensifies.

Problem:

- With insufficient analog headroom, pulse drives electronics into nonlinear operation. → spurious signals generated that corrupt undistorted pcal signal
- Options to avoid driving electronics into saturation:
  - Reduce pulse strength
    - Phase cal SNR reduced → noisier phase extraction
    - More prone to contamination by spurious signals
  - Reduce pulse strength *and* increase pulse repetition rate to 5 or 10 MHz
    - Fewer tones spaced 5 or 10 MHz apart
- With 5 or 10 MHz rep rate, baseband tone frequencies can differ from channel to channel when channel separation = 2^N MHz.
  - Fringe-fitting is more complicated if only one tone per channel is extracted .
  - Software solution: Use multiple tones per channel and correct for delay within each channel, as well as between channels.

Source: Brian Corey; Tecspec-Meeting 2012

Pulse repetition rate and headroom

- As RF bandwidth increases, pulse intensifies.
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- Options to avoid driving electronics into saturation:
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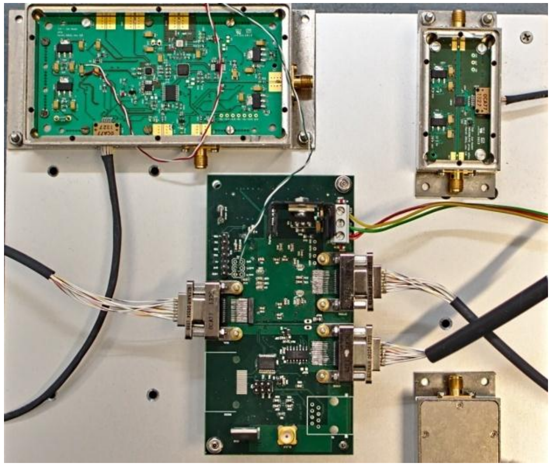
  - Fringe-fitting is more complicated if only one tone per channel is extracted .
  - Software solution: Use multiple tones per channel and correct for delay within each channel, as well as between channels.
- General recommendation: peak pcal pulse power / P1dB < -10 dB

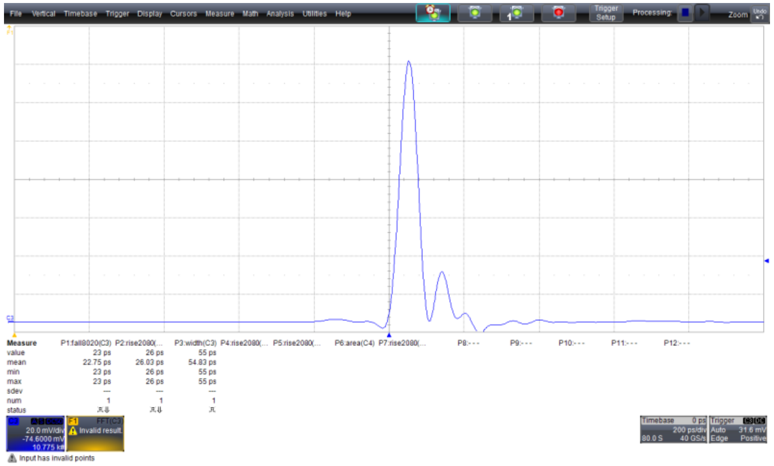
Source: Brian Corey; Tecspec-Meeting 2012

Design Status Phasecal-Unit TTW

Pcal Development-System



Phasecal-Pulse in Time Domain



Measure	P1:fall8020(C3)	P2:rise2080(...	P3:width(C3)	P4:rise2080(...	P5:rise2080(...	P6:area(C4)	P7:rise2080(...	P8:---	P9:---	P10:---	P11:---	P12:---
value	23 ps	26 ps	55 ps									
mean	22.75 ps	26.03 ps	54.83 ps									
min	23 ps	26 ps	55 ps									
max	23 ps	26 ps	55 ps									
sdev	---	---	---									
num	1	1	1									
status												

C3: 20.0 mV/div, -74.6000 mV, 10.775 k

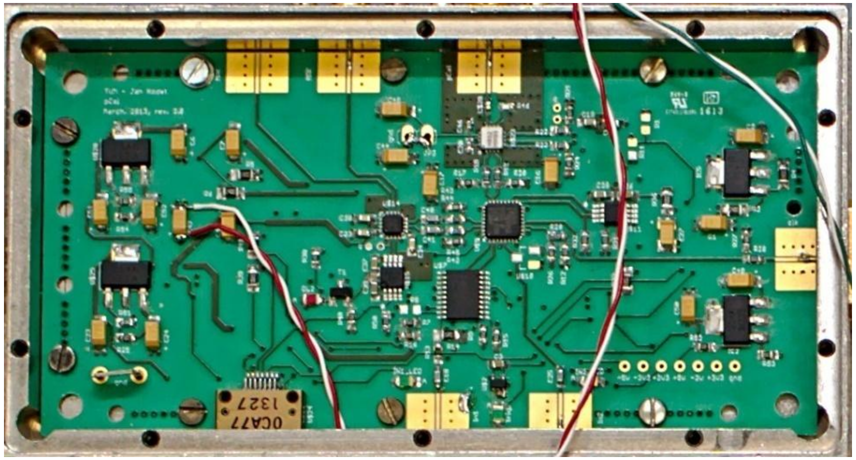
F1 FFT(C3): ⚠ Invalid result.

⚠ Input has invalid points

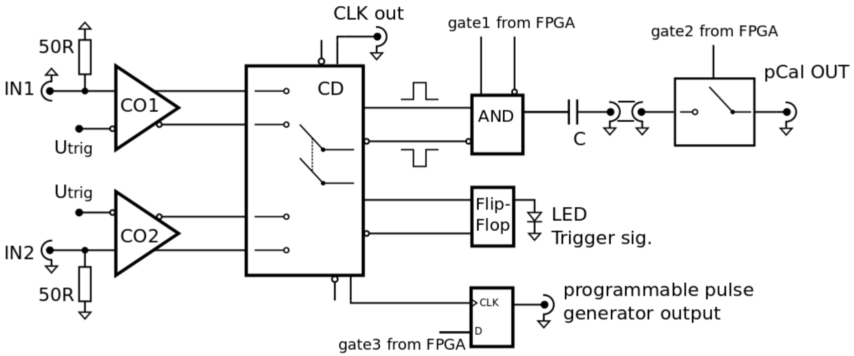
Timebase 0 ps, 200 ps/div, 80.0 S 40 GS/s

Trigger C3 DC: Auto 31.6 mV, Edge Positive

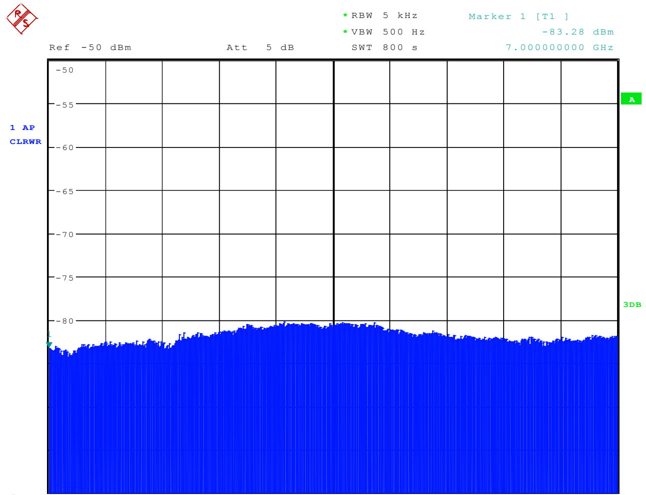
Phasecal-PCB

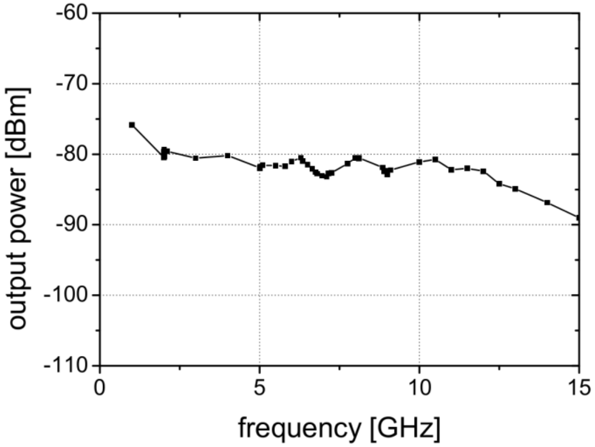


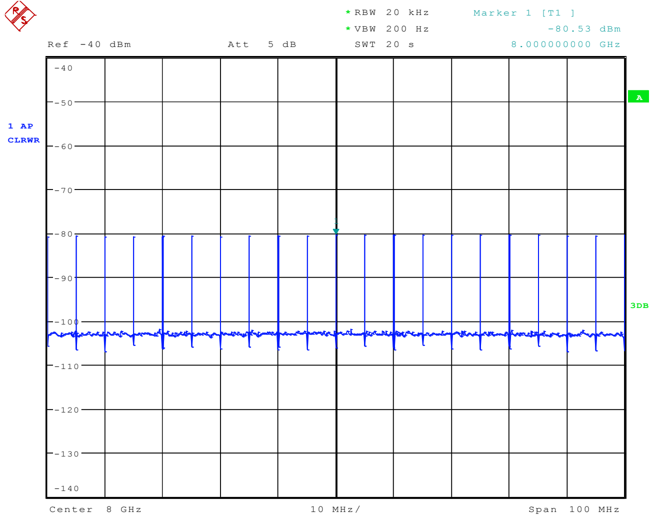
Blockdiagramm New Phasecal Unit



New TTW Phasecal Power Level







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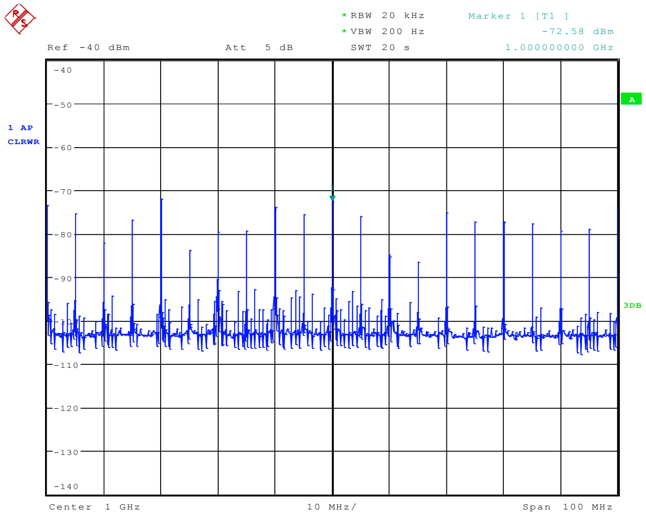
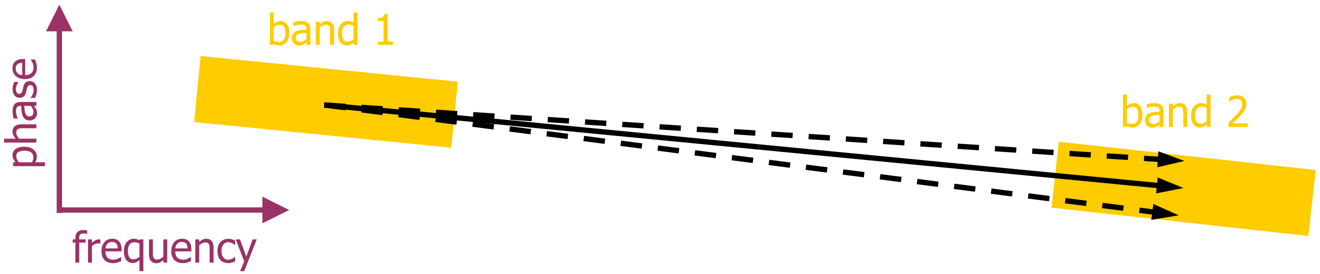


Date: 16.JAN.2014 18:18:00

Spec for spurious signals independent of antenna orientation



- Case 1: To create bbdelay, must extrapolate phase between two bands up to 5 GHz apart.
  - Require extrapolated phase to be precise to < 1/10 radian.
  - → delay error < 0.1 / (2π×5 GHz) = 3 ps
  - 3-ps delay = 0.02 radian (1) over 1 GHz, or 0.01 radian over 500 MHz
- Case 2: One fall-back option is to use group delay over 3 contiguous bands.
  - For SNR = 20, σ(group delay) ≈ 10 ps.
  - Want instrumental error << σ. → instrumental error < 1 ps.
  - 1-ps delay = 0.02 radian over 3 GHz
- Specification for spurs that do not depend on antenna orientation:
  - Sufficient condition: spurs < -40 dB relative to pcal
  - Necessary condition: delay error < 3 ps over 1 GHz and < 1 ps over 3 GHz

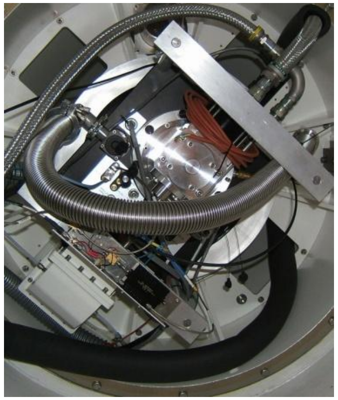
Source: Brian Corey; Tecspec-Meeting 2012

Spec for spurious signals dependent on antenna orientation

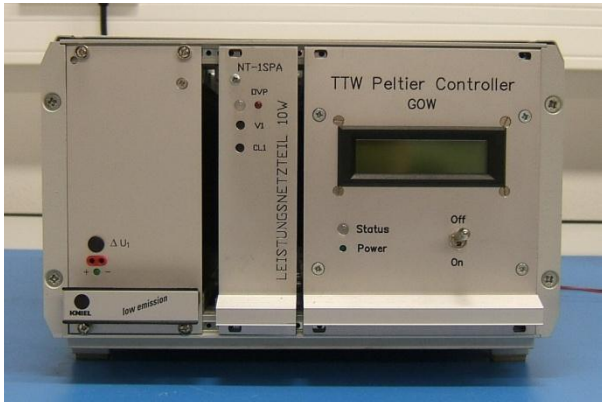
- Spurs that vary systematically with antenna orientation need their own spec.
- Possible origins:
  - Varying multipath affecting pcal radiated (intentionally or not!) into feed
  - Elevation-driven thermal variations in pulse generator
- VLBI2010 goal is 1-mm 3-D station position accuracy in 24 hours.
- Orientation-dependent systematic errors…
  - map into station position, and therefore
  - should be kept < 0.1 mm = 0.3 ps.
- 0.3 ps error can arise from spur-induced phase error of
  - 0.004 radian at 2 GHz (broadband delay case), or
  - 0.006 radian change over 3 GHz (case 2 of previous slide).
- Specification for spurs that vary with antenna orientation:
  - Sufficient: spurs < -50 dB relative to pcal
  - Necessary: phase error < 0.004 radian & delay error < 0.3 ps over 3 GHz
- Simulations of subreflector-feed multipath indicate that -50 dB spec is more restrictive than necessary for path length changes < a few cm.

Source: Brian Corey; Tecspec-Meeting

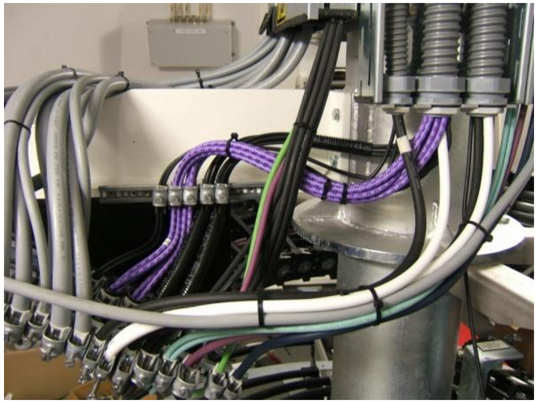
Other TWIN Projects



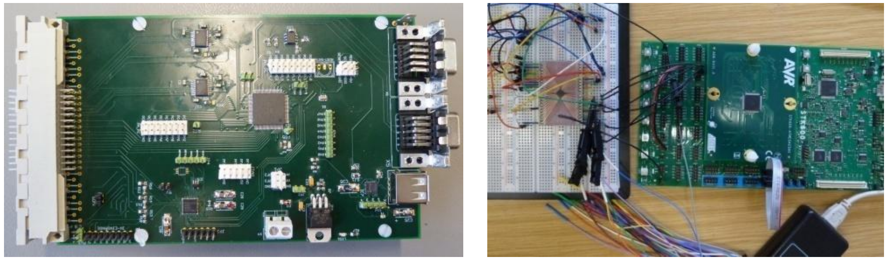
S/X/Ka-Band Empfängers



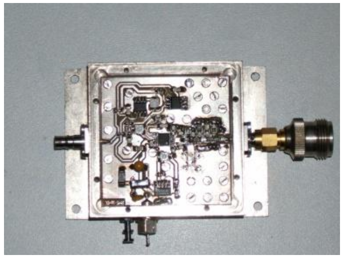
Peltier-Controller für Pcal



Wideband-cable track TTW1



Prototypeboard Monitoring System and A/D Converter

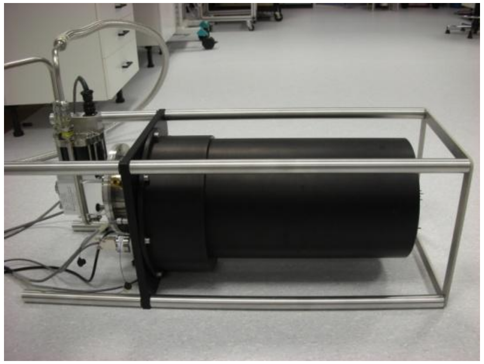


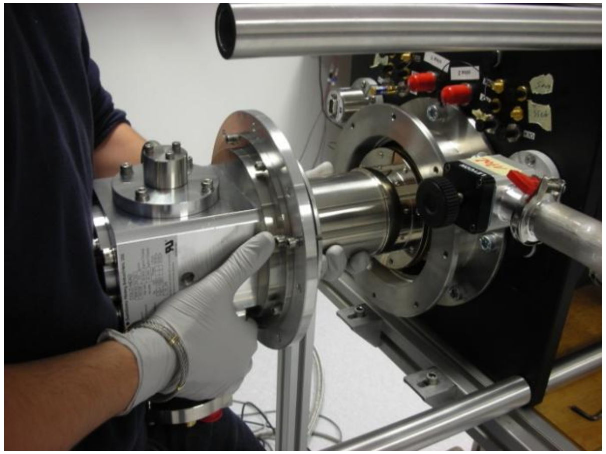
RMS-DC Converter

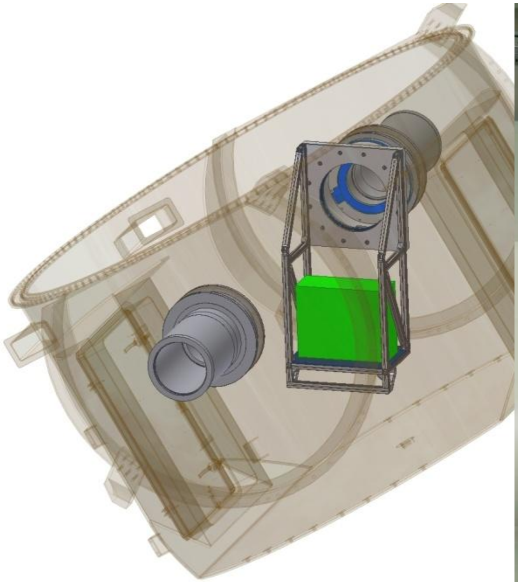
RF-Equalizer

Other topics: Cyrogenic design

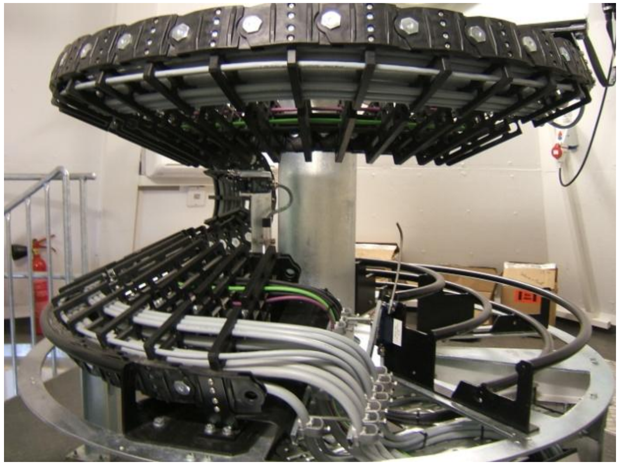
- Cooled LNA and Feeds are necessary, but how to get the heat out of the cabin?
- How to mount the Helium Compressor in the Elevation cabin?
- How to do a coldhead cylinder maintenance without removing the whole feed?







Other topics:
Cable warp and feed blower



- Choosing a cable wrap for 1000 observations a day and a high drive velocity
- Choosing RF-cables for the signal and for the frequency reference
- Choosing fiber cables for a cable wrap and 1000 bend cycles
- How to prevent the feed foils from rain, snow and ice ?

- and so on ….

Energy Saving

- Green Mode Observation
- Loading the deceleration energy back into the power network
- Heat transfer from the electronic devices and servers to warm up the main building
- Good thermal isolation of the main building and the towers

Thank you!