Practical issues in writing a technical specification for a radio telescope

Hayo Hase, BKG
Content

- Basics of a radio telescope project
- Defining the optics
- Radio telescope as a geodetic monument
- Radio telescope as a mechanical instrument
- Requirements for design and construction
- Other subjects
# Phases of a radio telescope project

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Technical specification</td>
<td>3 months – 1 year</td>
</tr>
<tr>
<td>2. Invitation for tenders, preparation of the offer</td>
<td>3 months</td>
</tr>
<tr>
<td>3. Signing a contract</td>
<td>1 day</td>
</tr>
<tr>
<td>4. Design</td>
<td>3 months – 1 year</td>
</tr>
<tr>
<td>5. Design review</td>
<td>2 days – 1 week</td>
</tr>
<tr>
<td>6. Production and delivery</td>
<td>1 – 3 years</td>
</tr>
<tr>
<td>7. Acceptance tests</td>
<td>3 months – 1 year</td>
</tr>
<tr>
<td>8. Handing over of responsibility</td>
<td>1 day</td>
</tr>
</tbody>
</table>

Σ = 2 – 5 years

*blue = customer, red = contractor, black = both*
Project management

- Brainstorming
  - Collection of ideas
- Evaluation of ideas
  - Technical challenge
  - Cost
  - Usefulness
- Consensus

Discussion avoids errors

Meet the experts needs inspiration, knowledge and some experience
Motivation

- challenge “Global Geodetic Observing System”
  - global reference frame with relative precision of $10 \times 10^{-9} \Rightarrow \text{the millimeter}$ on global scale
  - Earth orientation monitoring 24h/7d during lifetime of 20 years
- requires new construction of radio telescopes for geodetic VLBI
Applicable Documents


IVS VLBI2010 documents can be found here: http://ivscc.gsfc.nasa.gov/technology/vlbi2010-documents.html
Sketch of the components
Visualization of dimensions
Acronyms and Definitions

- List of all acronyms in the techspec
- List of all definitions
  - antenna: comprises the complete receiving system, synonym for radio telescope
  - brown out: voltage of one or more phases in electrical power supply lines is below nominal, but not zero
  - etc.
## Project Plan

<table>
<thead>
<tr>
<th>Activity</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
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</thead>
<tbody>
<tr>
<td>Projectmanagement</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Site acquisition</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Twin-Telescope (this document)</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Call for bids</td>
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<tr>
<td>Design</td>
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<td>Construction of parts</td>
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<td>Assembling at Wettzell</td>
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<td><strong>Buildings, foundations</strong></td>
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<tr>
<td>Planning</td>
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<tr>
<td>Construction</td>
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<td><strong>HF-Components</strong></td>
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<td>Call for bids</td>
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</tr>
<tr>
<td>Construction, delivery</td>
<td></td>
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<tr>
<td><strong>Data Acquisition</strong></td>
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<td>Construction, delivery</td>
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<tr>
<td><strong>Radiometer</strong></td>
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<td></td>
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<tr>
<td>Call for bids</td>
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<tr>
<td>Construction, delivery</td>
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<tr>
<td><strong>Acceptance, finalization</strong></td>
<td></td>
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</tbody>
</table>
Scope of this document

- The specification establishes the performance, design, development and test requirements, which apply to the Twin Telescope Wettzell.

- Options
  - larger diameter
  - backup structure on carbon fibre or composites

- Responsibilities
  - who is doing what?
Content of a Technical Specification

0. General Informations
1. Scope of this document
2. Acronyms and Definitions
3. Applicable Documents
4. Functional and Performance Requirements
5. Antenna System Requirements
6. Subsystem Requirements
7. Integration, Service, Transport, Testing
8. Reliability, Maintainability, Safety Requirements
9. Requirements for Design and Construction
10. Operation Building
11. Documentation
12. Verification and Quality Assurance
13. References

This is just an example. Any other structure will do it.
Content

- Basics of a radio telescope project
- **Defining the optics**
- Radio telescope as a geodetic monument
- Radio telescope as a mechanical instrument
- Requirements for design and construction
- Other subjects
Defining the optics

- 100% atmospheric opacity
- 0%

Microwave window

Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gases (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.
How to start with the design?

“The design of a radio telescope starts with the feed.”

Richard Kilger
S/X dualband vs. broadband feed

Broadband spectrum feed is characterized by a wider illumination angle.
Defining the parabola by $f/D$

<table>
<thead>
<tr>
<th>$f/D$</th>
<th>ex.</th>
<th>$\theta/2$</th>
<th>$\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td></td>
<td>53.1°</td>
<td>106.2°</td>
</tr>
<tr>
<td>0.45</td>
<td>Wz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>Oh</td>
<td>64.0°</td>
<td>128.0°</td>
</tr>
<tr>
<td>0.36</td>
<td>Tc</td>
<td>69.5°</td>
<td>139.0°</td>
</tr>
<tr>
<td>0.30</td>
<td>TTW</td>
<td>79.6°</td>
<td>159.2°</td>
</tr>
</tbody>
</table>

D = 12.0 m

Illumination angle
Primary focus vs. secondary focus

- only one reflection, less signal loss
- feed points to the cold sky
- receiver indoors
- maintenance easier

receiver in the air

receiver indoors
Minimizing shadowing effects
12m secondary focus system

- Ring focus design

- Illumination

- Losses by legs and horn
- Minimized loss by legs
- Loss by horn
- Full illumination of parabola
  - No loss by horn/subreflector
Advantages of ring focus design

- Rays from main reflector rim illuminate the pointed vertex of the subreflector
- Rays from main reflector central area illuminate the subreflector rim
- Minimum reflection of energy towards the feed horn
- Feed horn can be positioned close to the subreflector as needed for wide-band feed
Summary Optics

1. Design of a radio telescope starts with the feed for $\nu = 2..14$ GHz.

2. Broadband feeds for VLBI2010 have a wide opening angle.

3. Ring focus optics appears to be optimal for wide angle broadband feeds.

4. The reflector diameter should be approx. 12m (VLBI2010).

5. The $f/D$ follows to be approx. 0.3.
Antenna structure performance

- frequency range: $\nu = 2 \ldots 40$ GHz resp. $\lambda = 15$ cm .. 7.5 mm
- surface accuracy: rms $< 0.2$ mm
- systematic pointing error: rms $< 20$ arcsec
- non-systematic pointing error: rms $< 3$ arcsec
- path length error: rms $< 0.3$ mm

Rule of thumb:
- $< \lambda / 10$
- $10\%$ beamwidth
  - beamwidth $= 70 \lambda / d$
Reflector surface error

- deviation from ideal parabolic surface caused by:
  - panels
  - backing structure
  - panel mounting
  - subreflector

- due to:
  - manufacturing
  - ageing
  - gravity
  - wind, temperature and temperature gradients
  - alignment

APEX, ±14.7µm rms
VLBI2010: < 200 µm
holographic image, 92.4 GHz
Pointing error

- difference between commanded position of the radio telescope and the actual position of the max. RF beam
  - repeatable errors can be modeled and are caused by
    - gravity deformation
    - axis alignment errors
    - encoder offsets
    - bearing runout, bearing alignment
  - non-repeatable errors cannot be modeled and are caused by
    - wind
    - temperature effects
    - accelerations forces
    - encoder resolution and encoder errors
    - servo and drive errors
    - position update rate

\[< 0.0055 \text{ deg}\]
\[< 20 \text{ arcsec}\]
\[< 0.0008 \text{ deg}\]
\[< 3 \text{ arcsec}\]
Path length error $< 0.3$ mm

Path length error $0.3$ mm = excess delay $1$ ps

- difference between the arrival time of a plane wave front at the invariant point of the radio telescope system (ideally intersecting axes) and at the secondary focus after two reflections.

Path length error has

- a **repeatable** component caused by material properties, axis alignment errors, bearing runout and alignment and

- a **non-repeatable** component caused by wind and thermal effects, bearing non-repeatability, accelerations forces and other sources.

The sum of both shall not exceed $0.3$ mm over the full azimuth and elevation range.

=> necessary condition for VLBI at 2—40 GHz (S-, X-, Ka, Ku-band), array mode of twin telescopes, and the 1 mm GGOS goal.
Pointing error vs. path length error
design optimization

- VLBI requests **minimum path length error**.
- **Pointing error** must be corrected by pointing model.
Subreflector

- subreflector must meet the surface accuracy budget
- hexapod positioner allows corrective positioning of subreflector
  - range: X,Y: ±10 mm, Z: ±15 mm
  - accuracy: ±5μm

Position must be logged and used in VLBI analysis.
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● Radio telescope as a geodetic monument
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● Requirements for design and construction
● Other subjects
Geodesists have to monitor the **sea level rise**, which requires a global geodetic reference network.

A radio telescope for geodetic VLBI must be an “error-free” reference point.
Measuring the changing Earth by VLBI

The radio telescope is a geodetic monument which has to provide a stable reference during the lifetime of about 20 years.
Forces acting on the radio telescope

- gravity
- wind
- temperature gradients
- snow
- ice
- corrosion
- acceleration by earthquakes
- acceleration by moving
• max. distance between azimuth and elevation axes: $0.0 \text{ mm} \pm 0.3 \text{ mm} \text{ tolerance}$
• orthogonality of azimuth and elevation axes: $< 10 \text{ arcsec}$
• max. distance between elevation axis and line of sight: $0.0 \text{ mm} \pm 0.3 \text{ mm} \text{ tolerance}$
• orthogonality of elevation axis and line of sight: $< 5 \text{ arcsec}$

A theodolite should be precisely aligned with the invariant point, allowing for materialization by geodetic targets.
Local survey

location of 20m radio telescope

geodetic network at Wettzell station

geodetic target mounted at intersection of azimuth and elevation axes

This is the end of the baselines.
Specification of ambient parameters

- **primary operating conditions** (full performance)
  - \( t = -20^\circ..+35^\circ C \), rain: 50 mm/h
  - wind: < 40 ±10 km/h gusts

- **secondary operating conditions** (tolerated degradation of performance)
  - \( t = -25^\circ..+40^\circ C \), rain: 100 mm/h
  - wind: < 100 ±30 km/h gusts

- **survival stow conditions** (temporarily parked at safe position)
  - \( t = -35^\circ..+45^\circ C \), rain: 100 mm/h
  - hailstones: \( d = 30 \text{ mm} \), \( v = 30 \text{ m/s} \)
  - radial ice on all exposed surfaces: 30mm
  - snow: 100 kg/m²
  - wind: 180 km/h ±40 km/h gusts

These are the numbers for Wettzell! consider global warming effects for next 20 years here!
Daily temperature gradient

Example: 2012-01-01 Concepción

TIGO Concepción, Temperature [°C] Average per Minutes in CL time

max. = 33.8°C

ΔT = 23.2°C

min. = 10.6°C
Thermal linear expansion

\[ \frac{\Delta L}{L} = \alpha L \Delta T \]

<table>
<thead>
<tr>
<th>material</th>
<th>thermal coefficient ( \alpha ) ( \mu m/m K )</th>
<th>( \Delta L ) ( L=10 \text{ m} ) ( \Delta T = 10 \text{ K} )</th>
<th>( \Delta L ) ( L=10 \text{ m} ) ( \Delta T = 20 \text{ K} )</th>
<th>( \Delta L ) ( L=10 \text{ m} ) ( \Delta T = 55 \text{ K} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel</td>
<td>13.0</td>
<td>1.30 mm</td>
<td>2.60 mm</td>
<td>7.15 mm</td>
</tr>
<tr>
<td>concrete</td>
<td>14.5</td>
<td>1.45 mm</td>
<td>2.90 mm</td>
<td>7.98 mm</td>
</tr>
<tr>
<td>aluminum</td>
<td>22.2</td>
<td>2.22 mm</td>
<td>4.44 mm</td>
<td>12.21 mm</td>
</tr>
<tr>
<td>carbon fibre</td>
<td>0.7</td>
<td>0.07 mm</td>
<td>0.14 mm</td>
<td>0.39 mm</td>
</tr>
</tbody>
</table>

**daily temperature gradients**

**annual gradient primary operation conditions**

\[ t = -20^\circ \text{C}..+35^\circ \text{C} \]

Vertical monitoring of radio telescope is obligatory. Construction must consider heat shielding and insulation.

Height monitoring system
Example: Wettzell 20m RT

Radiotelescope Wettzell

Distribution of the 5 electronic sensors

Invariant point

\[ T_1 = \text{Temperature at the lower point of invar wire} \]
\[ T_2 = \text{Temperature at the center of the radiotelescope} \]
\[ T_3 = \text{Temperature at the upper point of invar wire} \]
\[ T_4 = \text{Temperature inside the concrete wall} \]

\[ L_5 = \text{Anchor below the 1 kg weight for inductive measurements} \]

Hollow azimuth axis allows installation of height monitoring system
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1 mm: Reducing random errors by reducing source switch interval

VLBI2010 Committee

1 mm 3D error

suggests source switch interval = 30s
VLBI2010: 30s slew/track cycles

kinematic parameters

**azimuth**
- range: -270°..+270°
- velocity: 12 deg/s
- acceleration: 3 deg/s²
- 180° turn ≈ 19s

**elevation**
- range: 0°..90° (180°)
- velocity: 6 deg/s
- acceleration: 3 deg/s²
- 90° turn ≈ 17s

axes move simultaneously

Each sky position can be reached within 20s!
### VLBI2010: Mechanical load

<table>
<thead>
<tr>
<th>IVS-R1</th>
<th>VLBI2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>24h/week</td>
<td>168h/week (continuous)</td>
</tr>
<tr>
<td>1000 observations/24h</td>
<td>2880 observations/24h (30s slew/track cycle)</td>
</tr>
<tr>
<td><strong>52.000</strong> observations/year</td>
<td><strong>1.051.200</strong> observations/year</td>
</tr>
</tbody>
</table>

In terms of radio telescope movements: **one year of VLBI2010 operation corresponds to 20 years of current IVS-R1 operations!**

Radio telescope must be very robust, mechanically very stable, bearings must be perfect and withstand the observation load.

**Mechanical performance of radio telescope must be improved by a factor of 20!**
Energy saving (Green mode)

- max. speed = max. energy consumption
- requests extension of field system command:
  \textit{source=}	extit{name, right ascension, declination, catalog epoch, start time}
- \textit{start time} is the time in the near future when recording starts.
- Radio telescope will arrive with adapted speed onsource at start time = green mode.
Critical part: Bearings

You never want to replace the bearings!

- bearing internal clearance ≈ 0.2 mm
- concentricity: < ±0.15 mm
- diameter depends on mass and loads

• supports vertical, horizontal loads, tilting moments;
• superior to ball bearings

Catalog: http://www.rotheerde.com/download/info/Rothe_Erde_GWL_GB.pdf
Critical part: Cable wrap

- different curvature radius
- cables fixed in bundles
- gravity pull cables down

- constant curvature radius
- cables individually fixed
Mass

- moving parts should be minimized in mass without prejudice to performance specifications
- moving parts should be balanced in all possible pointing positions by **counterweights** → center of mass coincides with azimuth axis
- safety demands: counterweights must have slightly more mass – in case of brake failure, telescope will come to rest in to zenith position
Lightening protection

TTW

sliding contact to bridge azimuth bearing
as part of the lightening arrester

lightening arrester above subreflector

ground wire
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● Requirements for design and construction
● Untouched subjects
Requirements for design and construction (1)

- **finite element method** structural analysis
  - **static analysis**
    - gravity load (stress and deflection)
    - emergency braking (stresses)
    - thermal deformation (common loads)
    - wind under operating conditions (deflection)
    - wind under survival conditions (stresses)
  - **modal analysis**
    - eigenfrequencies and eigenmodes
  - **wind analysis**
    - force distribution by primary conditions
  - **seismic analysis**
    - each spatial direction

defines
- material (type of steel)
- bearings in function of mass and loads
- design of structure
Requirements for design and construction (2)

- **stress analysis and load combination**
  - **operational condition**
    - gravity + thermal (sec.) + wind (20m/s)
  - **accidental condition**
    - gravity + thermal (sec.) + wind (30m/s) + emergency braking
  - **survival condition**
    - gravity + wind (65m/s)
    - gravity + thermal (-30°C) + wind (30m/s)
    - gravity + wind (30m/s) + icing + snow
    - gravity + seismic (max. likely earthquake) + wind (20m/s)
Requirements for design and construction (3)

- simulation of servo
  - azimuth controller
  - elevation controller
  - wind model

controller must minimize deviation: < 3 arcsec

same order of non-repeatable pointing error
The error budget

<table>
<thead>
<tr>
<th>Error source</th>
<th>worst case quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>azimuth bearing</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>elevation bearing</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>path length error</td>
<td>0.30 mm</td>
</tr>
<tr>
<td>reflector surface accuracy</td>
<td>0.20 mm</td>
</tr>
<tr>
<td>subreflector surface accuracy</td>
<td>0.10 mm</td>
</tr>
<tr>
<td>hexapod positioner</td>
<td>0.005 mm</td>
</tr>
<tr>
<td>RSS</td>
<td>± 0.43 mm</td>
</tr>
</tbody>
</table>
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Antenna control system

Modes of operation (PC-FS commands)

- **stop**, brakes on
- **standby**, brakes off
- **idle**, stop motion brakes on
- **shutdown**, idle caused by interlock
- **preset**, commanded position
- **startrack**, tracking right ascension, declination
- **program track**, tracking azimuth, elevation, epoch
- **stow**, maintenance position
- **survival**, allows stow pins in/out
- **handheld panel**, allows to drive without servo
- **hand crank**, allows to move manually

must allow to apply additional offsets during tracking for radiometry

See also PC FS interface: [http://ivscc.gsfc.nasa.gov/about/org/coordinators/nc/antdef2.PDF](http://ivscc.gsfc.nasa.gov/about/org/coordinators/nc/antdef2.PDF)
Lifetime and reliability requirements

- minimum lifetime: **20 years with 24h operation**
- mean time between failure (MTBF): **>3 years**
- failure:
  - unable to move one axis after corrective maintenance intervention of 2 hours by 2 staff
  - degraded pointing performance: >5 arcsec absolute, >2 arcsec offset
  - ACU computer failure
  - motor failure
  - cable wrap failure
  - UPS failure
Maintenance

- shall be mainly performed at (sub)assembly level by **exchange of replaceable units**
- periodic preventive maintenance
  - 4 hours/month for 2 staff
  - automatic lubrication
- overhaul: >10 years
- alignment of reflector: >5 years
Safety design requirements

- fire
- mechanical
- electrical
- hydraulic
- pneumatic
- toxic

with respect to norms and standards: ISO, IEC, DIN, etc.
Security

- protection against unauthorized personnel access
  - locks on cabinets, doors
  - caged access ladder
  - sensors monitoring status (i.e. “door open”) connected to the ACU
Documentation

- language: english
- electronic format: pdf
- hardcopy format: A4
- layouts: electronically readable
- drawings: ISO standards, metric units
- number of hardcopies: 3
- software: maintenance and upgrade installation manual
- full test and acceptance procedures
Quality assurance

- verification by **design**
  - contract phase, design review
- verification by **analysis**
  - design phase, design review
  - part of documentation
- verification by **test**
  - performance demonstration by measurements and tests
  - part of documentation

Hint: Create a matrix listing each suitable item which was specified and needs quality check.