Method and equipment for SKA-lo calibration

SKACH Consortium Winter Meeting

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Outline

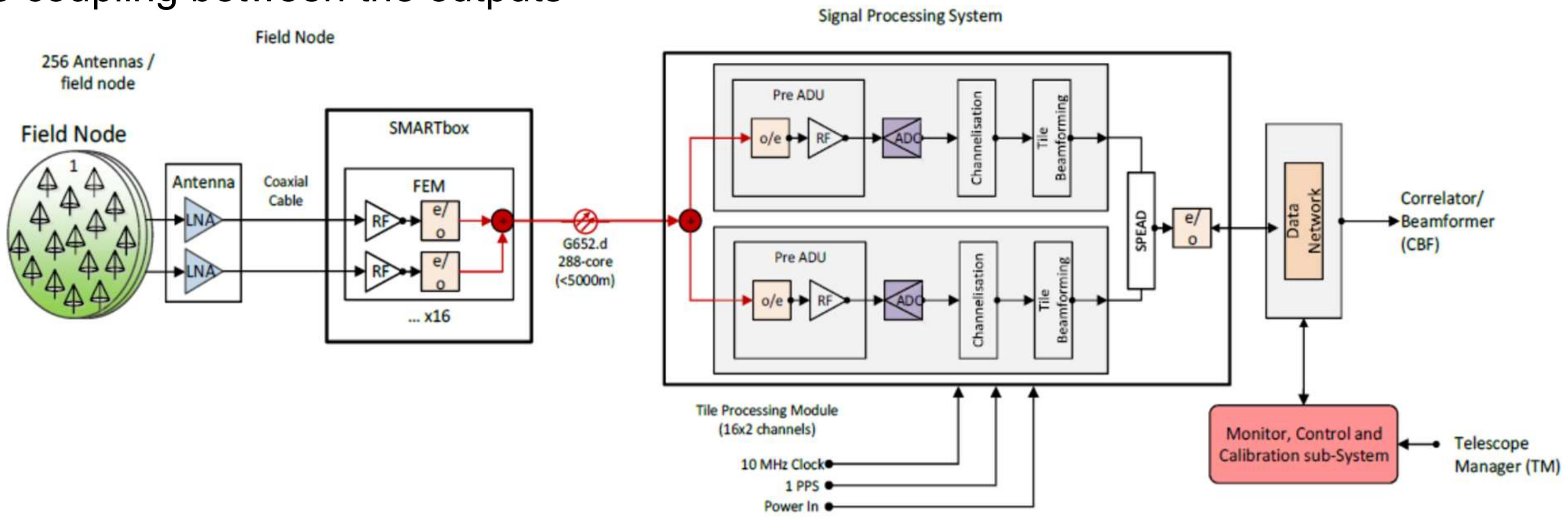
1. Calibration requirements
2. State-of-the-art of calibration methods
3. Our proposal : benefits and challenges
4. System design sketch
5. Next steps

1

Calibration requirements

Radio antenna calibration

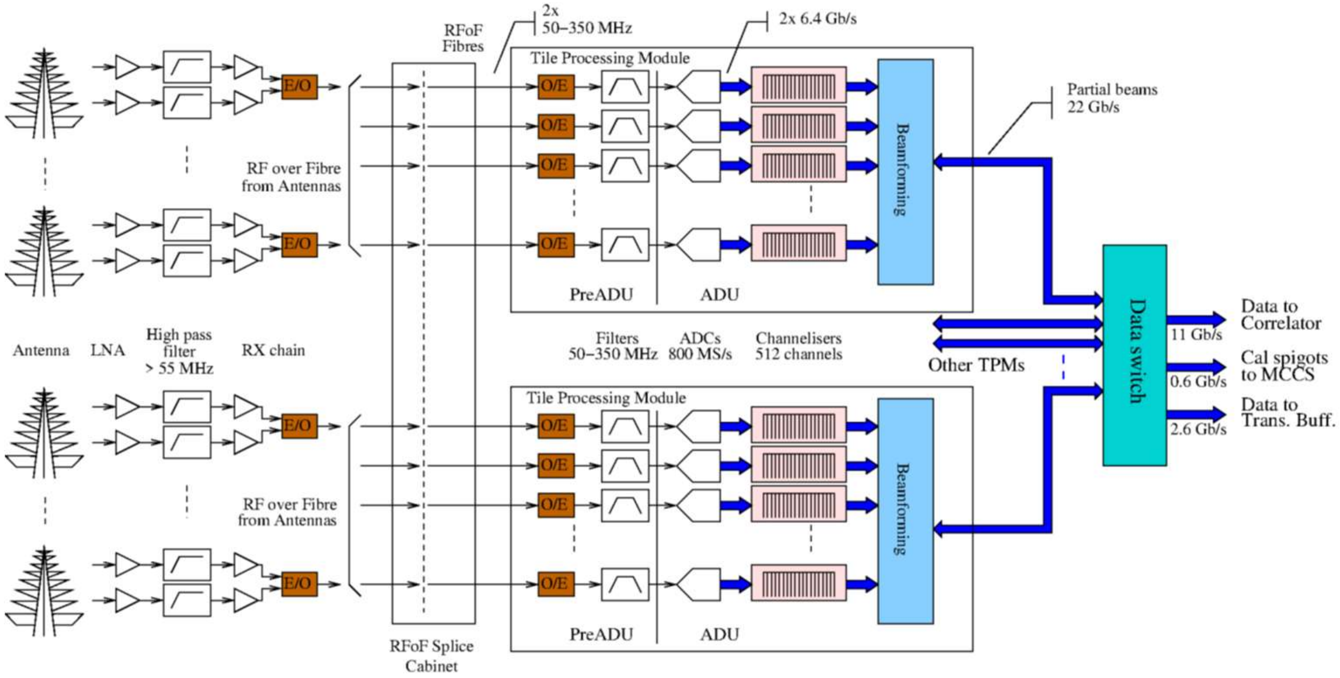
- Determine gain, phase and delay as a function of direction of arrival and of frequency of the incident electromagnetic wave
- For a dual polarization receiving antenna, determine the above for 2 different polarization outputs, as well as direction and frequency dependent polarization cross-coupling between the outputs



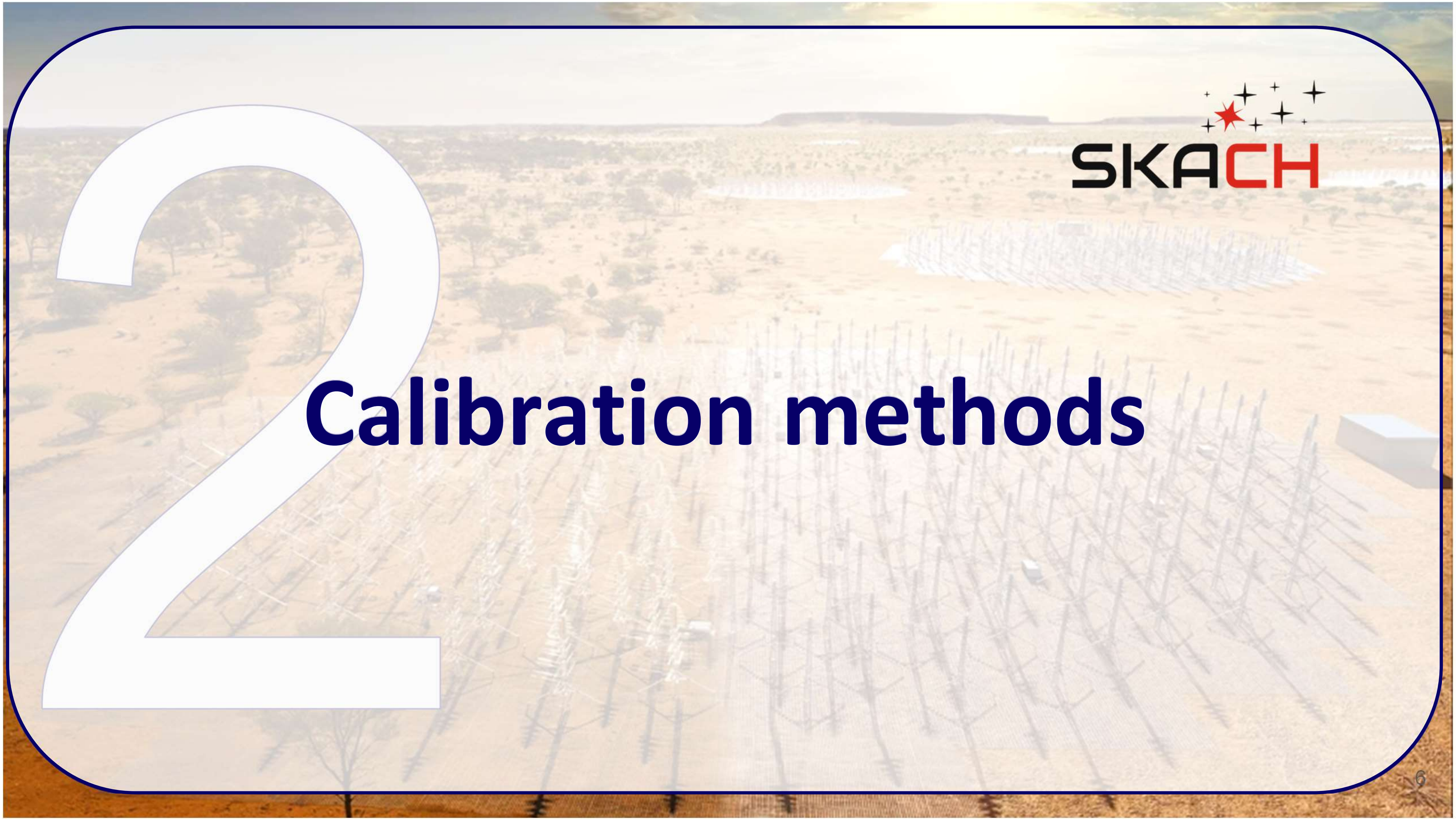
Signal chain block diagram [Report on the Station Calibration Task, SKA-TEL-SKO-0001088-02]

Telescope array calibration

- Calibrate the station beam, i.e. the digital delay and sum of antennae signals, as a function of direction of arrival
- In addition to individual antenna calibration, influence of antenna positioning and orientation, mutual coupling between antennae → Embedded Element Patterns (EEP)



[SKA-TEL-SKO-0001088-02]

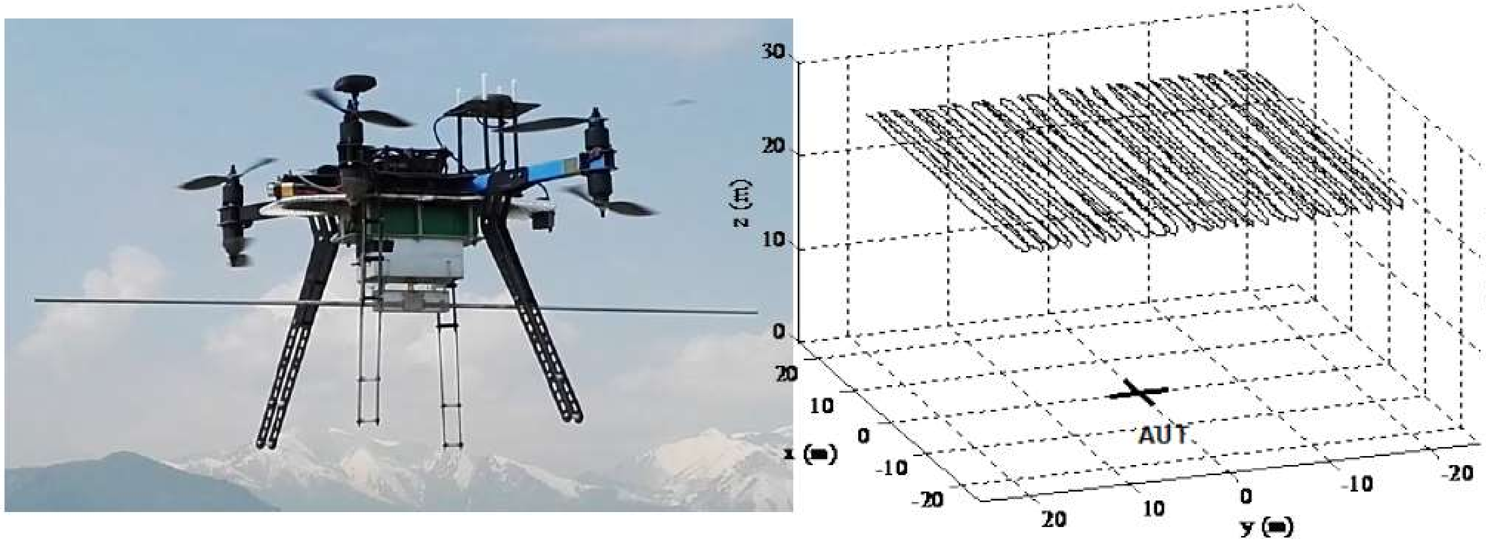


2

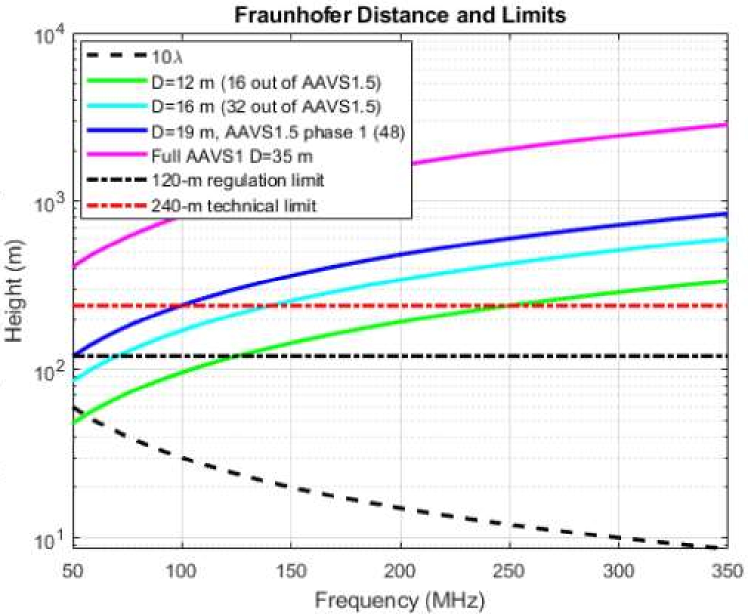
Calibration methods

Calibration with low-flying UAV based source

- Minimum Fraunhofer distance of station far field from antenna plane = $2D^2/\lambda$, D = 38m station diameter, λ_{min} = 0.86m (350MHz) → 3360m
- Since this cannot be realized with multicopters, only single element caracterizations, where the distance for far field condition e.g. >20λ, λ_{max} = 6m (50MHz) → 120m

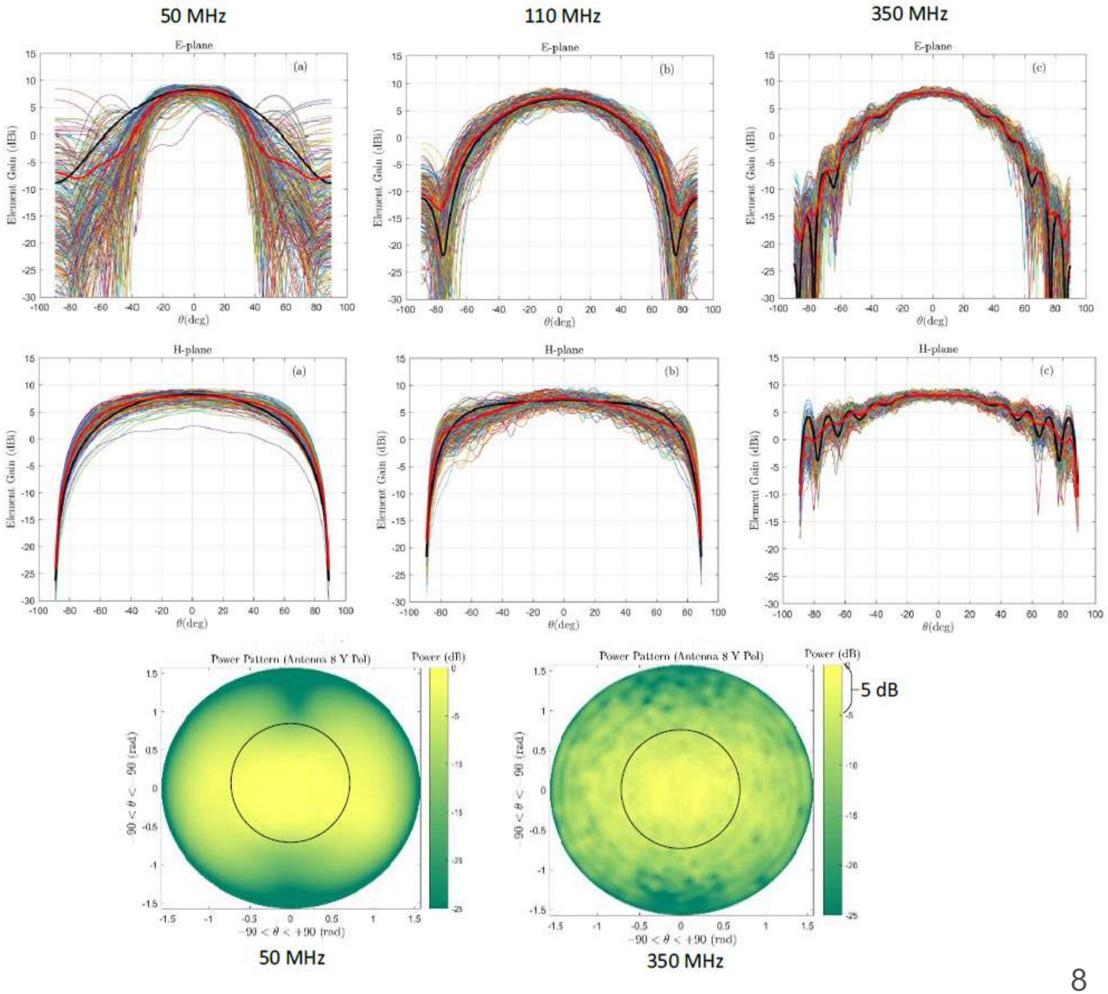


[SKA-TEL-SKO-0001088-02]



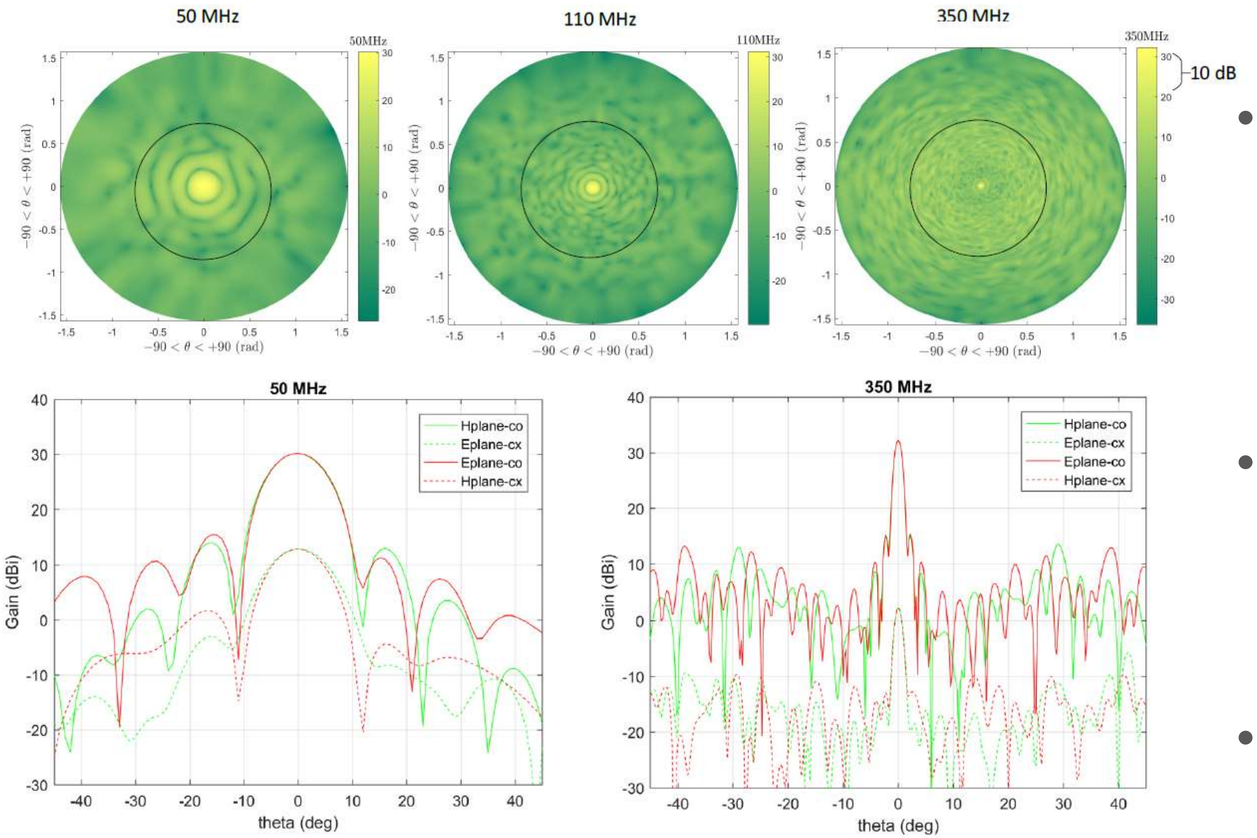
Embedded Element Patterns

- These results are simulated.
- Each line represents a different position in the array.
- E and H planes are vertical with respect to ground, and to each other.
- Black circle indicates intended field of view of ±45°.



[SKA-TEL-SKO-0001075-02]

Self holographic station beam calibration

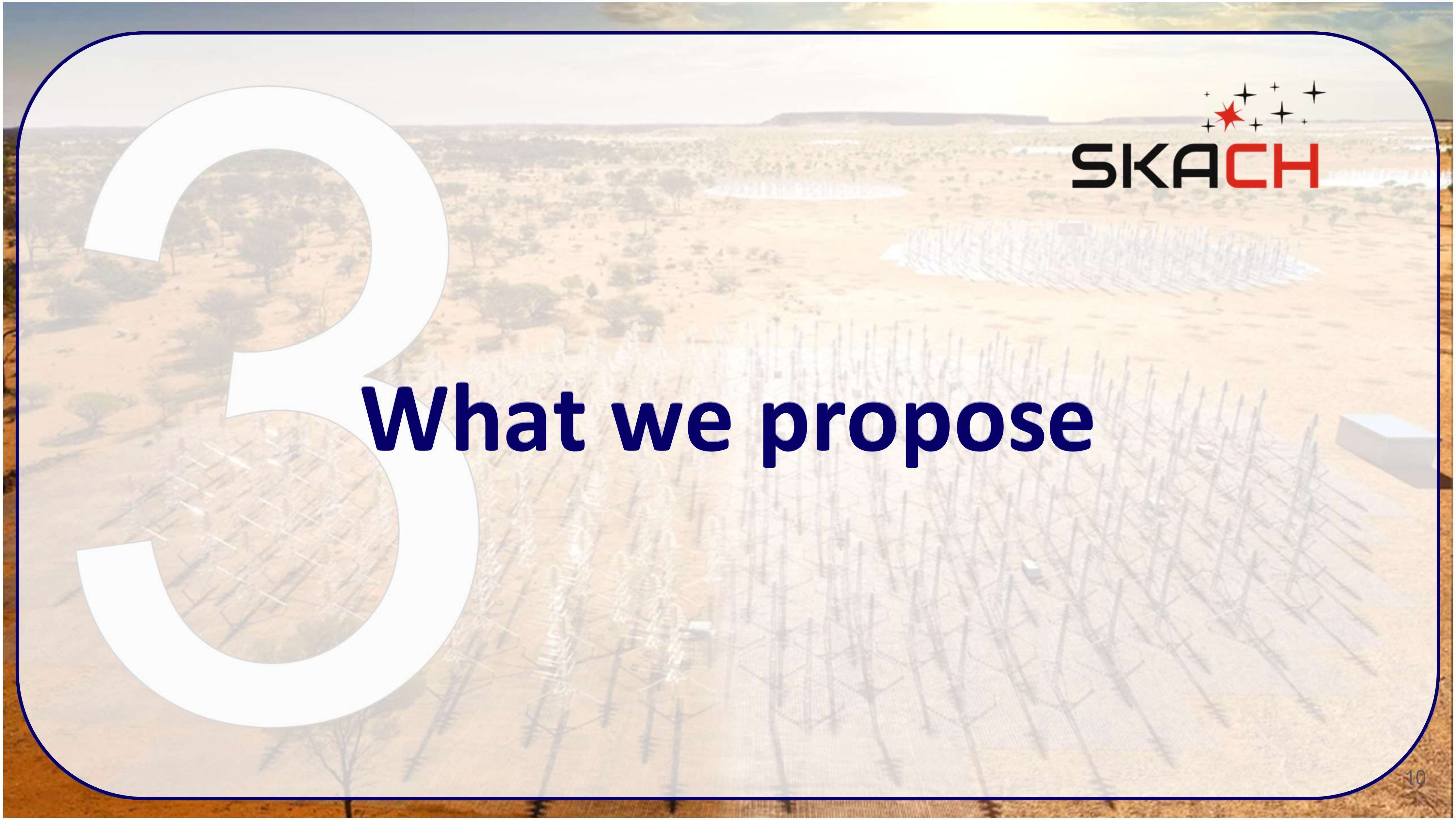


- Self holography is a method to compute antennae gains by correlation between the measured beam and an ideal reference beam.

- To be able to generate a gain map, the measured beam must be scanned through the field of view.

- Set a goal for experimental scans: e.g. ±60° from zenith.

Computed station beam [SKA-TEL-SKO-0001075-02]



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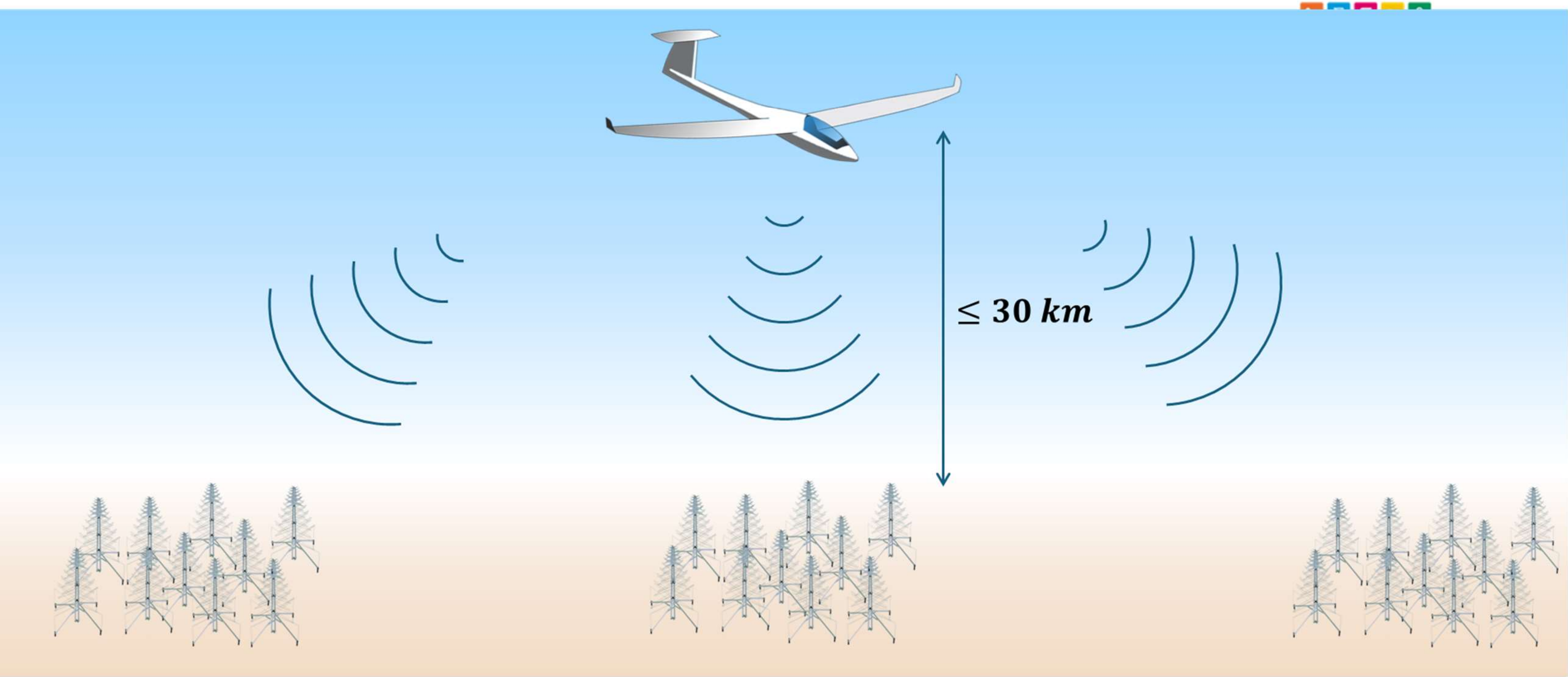
What we propose

Calibration by high-flying plane – the what



The Why

Advantages

- Observations are done with station antenna array, not with single independent receivers → calibration of array needed
- Straight wavefront in far field → calculation of element phases and delays can be done
- Mutual coupling effects inside the station array of antennae can be determined
- Non straight wavefronts due to atmospheric distortion, in particular close to antennae and in the ionosphere → such effects might be (partially) detected with a high flying calibrator

Challenges

- Environmental conditions at high altitudes are severe: at 30km, -60°C and 10mbar pressure (0.01atm)
- Energy for calibrator to be stored in batteries
- Calibration is with respect to field of view and frequency range: trade-off needed in the design of the calibrator path and flight duration
- Calibrator path, orientation, frequency and power must be recorded during flight
- Avoid RFI from UAV

Stratodynamics, **HiDRON Suborbital**

Balloon lift to 30km initial heigth

Gliding descent flight at glide ratio = 11, with ca. 80kmh, during 4h

Alternatives: electric stratospheric airplane, e.g. SolarStratos

Solarstratos
Solar power stratospheric powered flight

SOLARSTRATOS
TO THE EDGE OF SPACE

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System design sketch

Flight path – constant frequency operation

- Because of the continuous loss of altitude, and impossibility to fly sharp curves with reorienting the antenna, the path must be smooth.
- Circulating on a constant diameter maps into a spiral in E and H planes.
- Circle diameter such that 30° elevation from ground at 3360m distance, i.e rt(3)·3360m = 5820m
- At gliding ratio of 11, this allows for 16 turns between 30km and 3.36km.
- Table of viewing angles at the beginning of each circle:

h[km]	33.0	28.3	26.7	25.0	23.4	21.7	20.0	18.4	16.7	15.1	13.4	11.7	10.1	8.4	6.8	5.1
α [°]	5.54	5.86	6.22	6.63	7.10	7.64	8.26	9.00	9.87	10.9	12.3	13.9	16.1	19.1	23.3	29.7

- To cope with non-linear angle distribution, conical scan to be designed, with increasing diameter
- But this will reduce the number of turns, e.g. to 10.

Flight path – variable frequency operation

- To limit the number of flights, vary frequency during flight
- Frequency chirping is electronic = fast, but to keep antenna pattern simple, mechanical dipole length variation needed
- 2 frequency scan periods (up and down cycle) per flight circle would be a compromise solution
- With 14min per circle, ca. 7min per frequency scan, i.e. 3.5min per frequency chirp
- Another alternative: ramp up the frequency from 50MHz to 350Mhz while dropping from 30km initial altitude. Requires more complex flight path.
- Assumption : 10 frequency steps of 30MHz each. For each step design a flight path that occupies optimally the angle space.

What kind of power would we like to receive?

Antenna gain ~7 dB (log-periodic antenna typical gain)

LNA (from SKA-TEL-SKO-0001099, 2020-04-07)

Parameter	Typical
Frequency range	50 – 350 MHz
Gain	$\geq 40\ dB$
P1dB	$-30\ dBm$

$-88\ dBm \rightarrow -93\ dBm$ (with antenna gain $5\ dB$)

SKA-TEL-SKO-0001075-02 (DesignBaselineDescription)

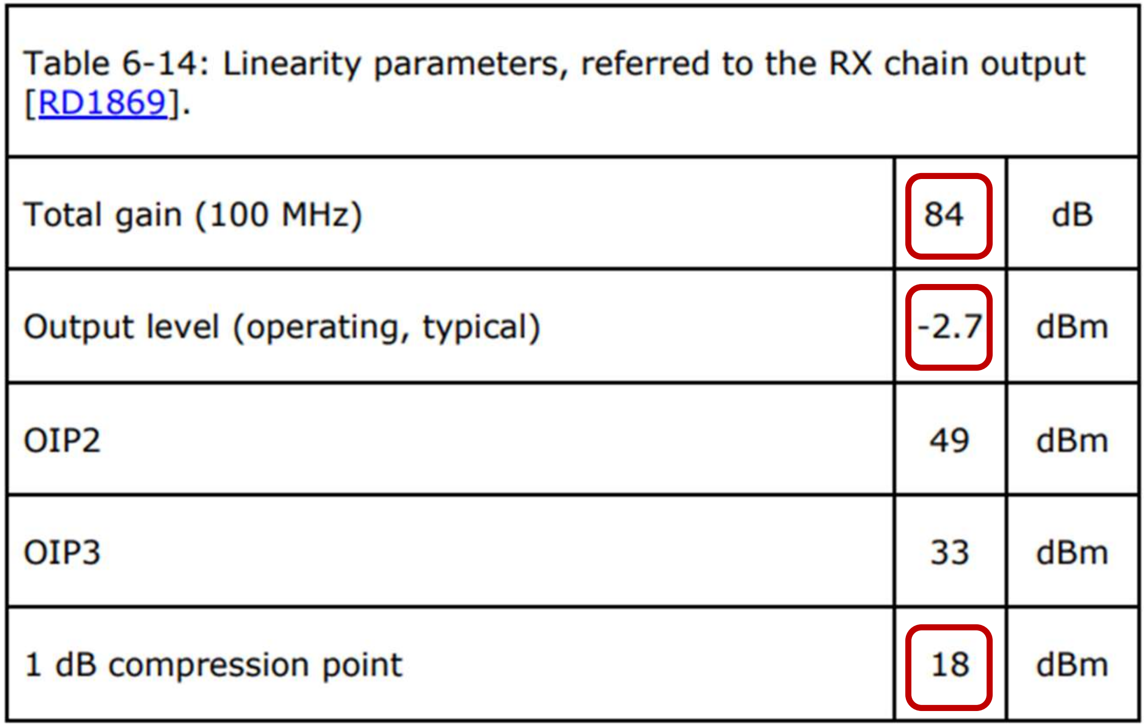


Table 6-14: Linearity parameters, referred to the RX chain output [RD1869].

Total gain (100 MHz)	84	dB
Output level (operating, typical)	-2.7	dBm
OIP2	49	dBm
OIP3	33	dBm
1 dB compression point	18	dBm

$-84\ dBm \rightarrow -93\ dBm$ (with antenna gain $5\ dB$)

What would we need to transmit?

$$\frac{P_r}{P_t} = 20\log_{10}\left(\frac{\lambda}{4\pi d}\right) = 20\log_{10}\left(\frac{c}{4\pi d f}\right) \to -96\ dB\ @\ 50\ MHz, 30\ km$$

Can just keep power constant and augment frequency while descending to keep losses constant

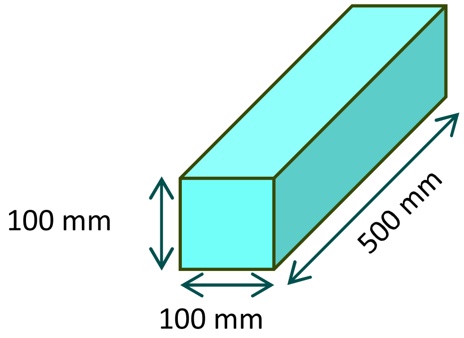
$-88\ dBm\ \to -93\ dBm$ (with antenna gain 5 dB)

Transmission power around 3 dBm

Constant frequency flight			
Frequency	Altitude	Attenuation	Trans. Power
$350\ MHz$	$30\ km$	$-113\ dB$	$20\ dB$
$350\ MHz$	$15\ km$	$-107\ dB$	$14\ dB$
$350\ MHz$	$7.5\ km$	$-101\ dB$	$8\ dB$
$350\ MHz$	$4.3\ km$	$-96\ dB$	$3\ dB$

Variable frequency flight			
Frequency	Altitude	Attenuation	Trans. Power
$50\ MHz$	$30\ km$	$-96\ dB$	$3\ dB$
$100\ MHz$	$15\ km$	$-96\ dB$	$3\ dB$
$200\ MHz$	$7.5\ km$	$-96\ dB$	$3\ dB$
$350\ MHz$	$4.3\ km$	$-96\ dB$	$3\ dB$

Drone payload and transmission antenna



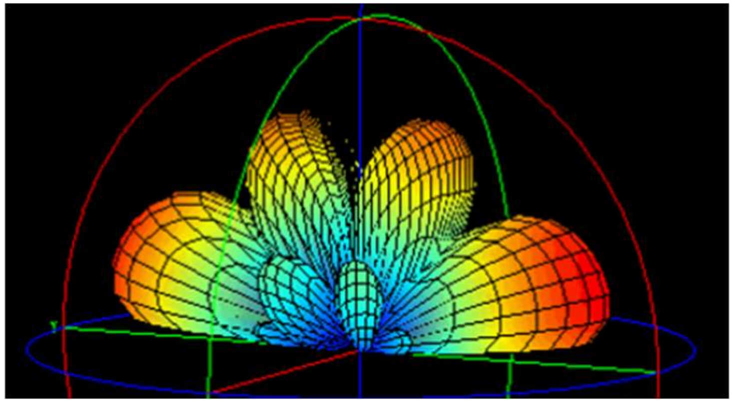
Calibration frequencies

$$f = 50\,MHz \rightarrow 350\,MHz$$

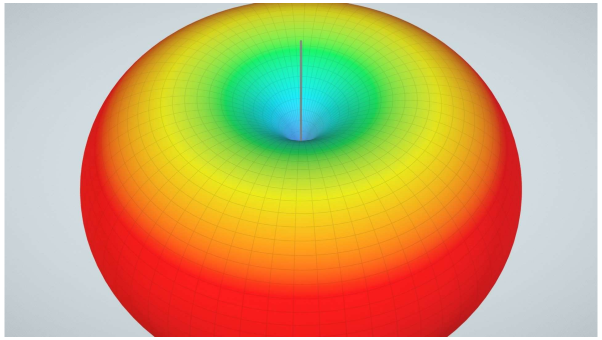
$$\lambda = 6\,m \rightarrow 0.86\,m$$

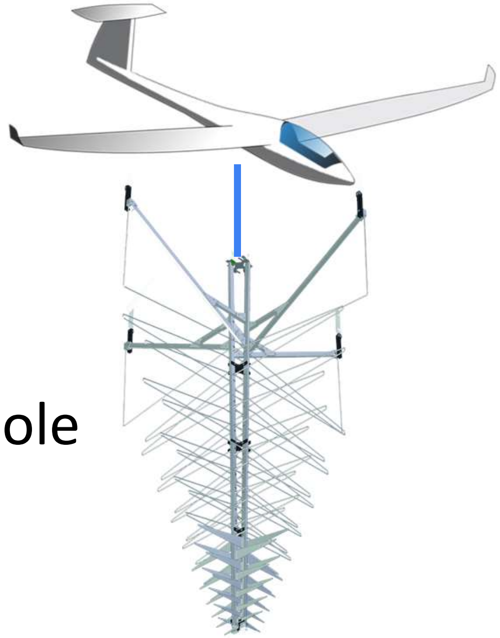
I would like a small, light-weight, omni-directional, wideband antenna with decent radiation efficiency, please.

Avoid the mess



Make a nice, resonant dipole

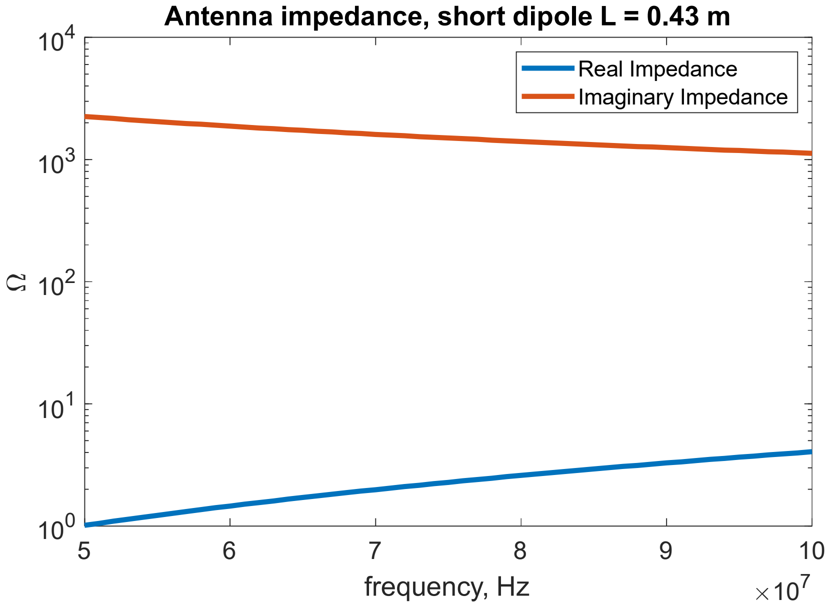


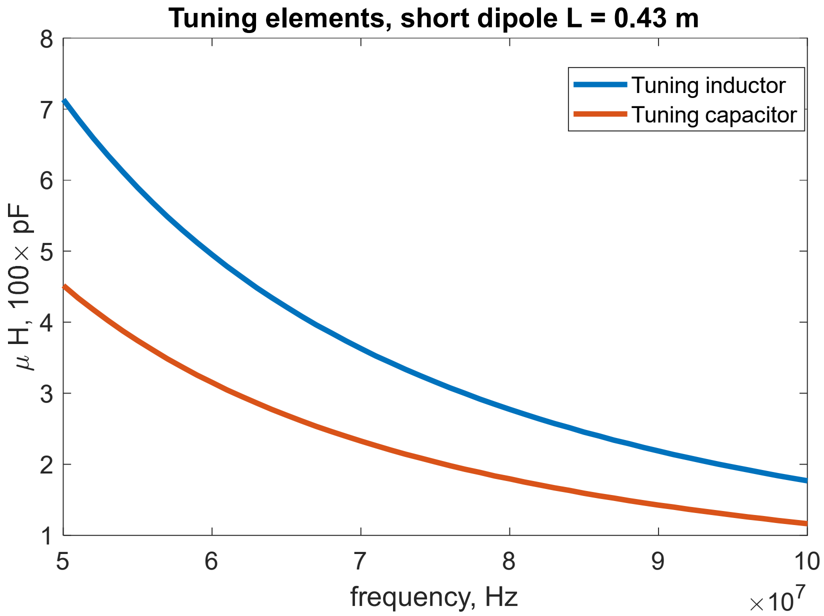


Too heavy,
too big

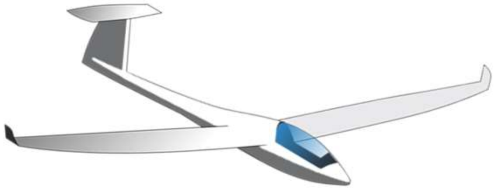
How about a short dipole?

- Length: 0.43 m, resonant at 350 MHz
- Extremely large reactance and small resistance
- Tuning elements hard to implement
- Large losses in inductance

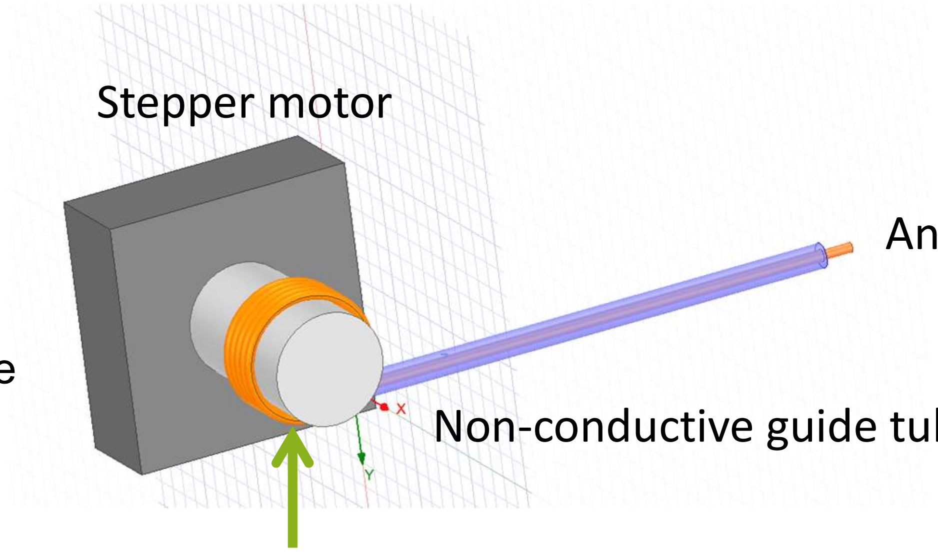




Tuneable dipole in the wings



- Use a wire guided by a rigid non-conductive tube to adjust length with a stepper motor.
- Can transmit any frequency that we can length-adjust for with a near-constant impedance



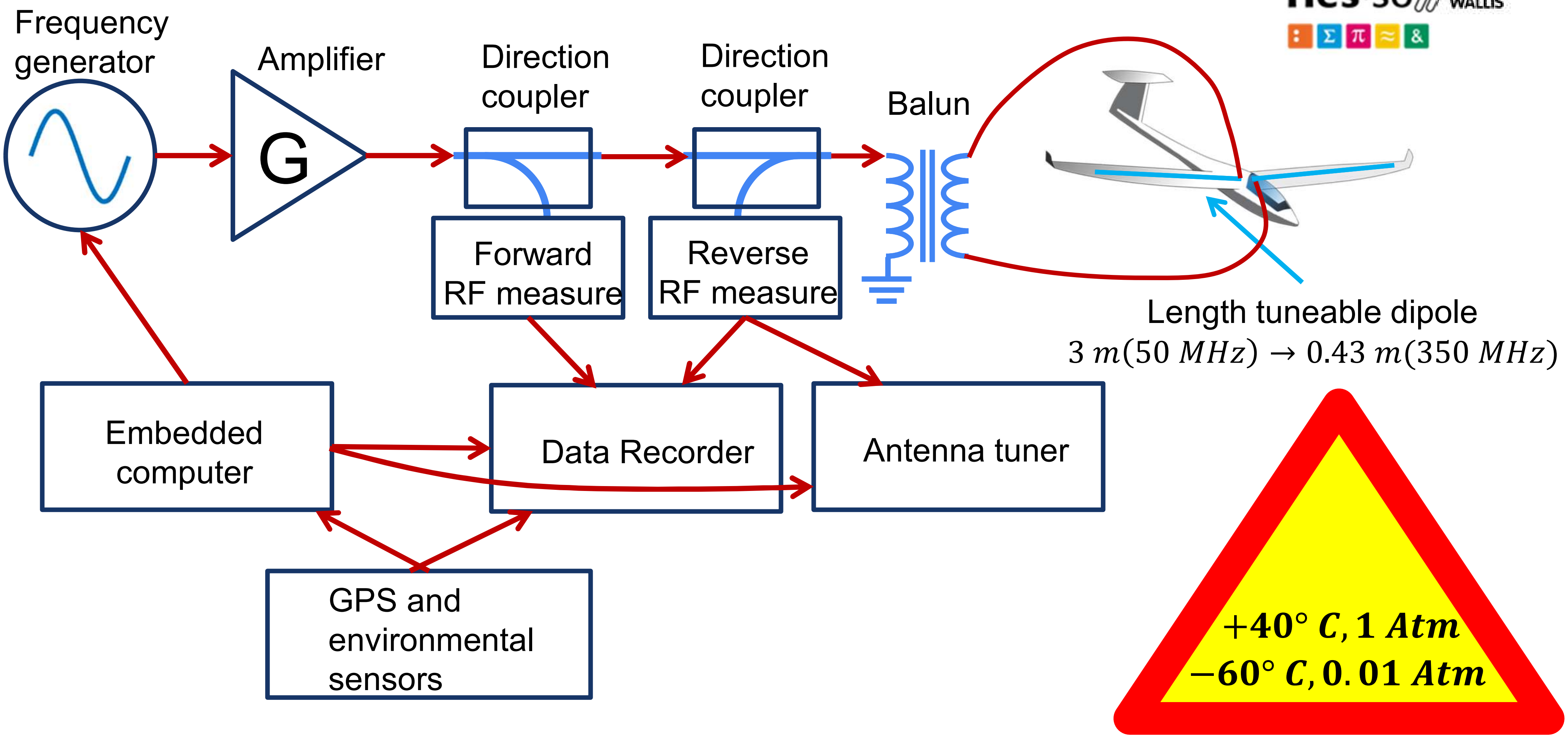
Stepper motor

Antenna, guided wire

Non-conductive guide tube

Feed-point

Transmission signal chain



Frequency generator

Amplifier

G

Direction coupler

Direction coupler

Balun

Forward RF measure

Reverse RF measure

Length tuneable dipole

$3\ m(50\ MHz) \rightarrow 0.43\ m(350\ MHz)$

Embedded computer

Data Recorder

Antenna tuner

GPS and environmental sensors

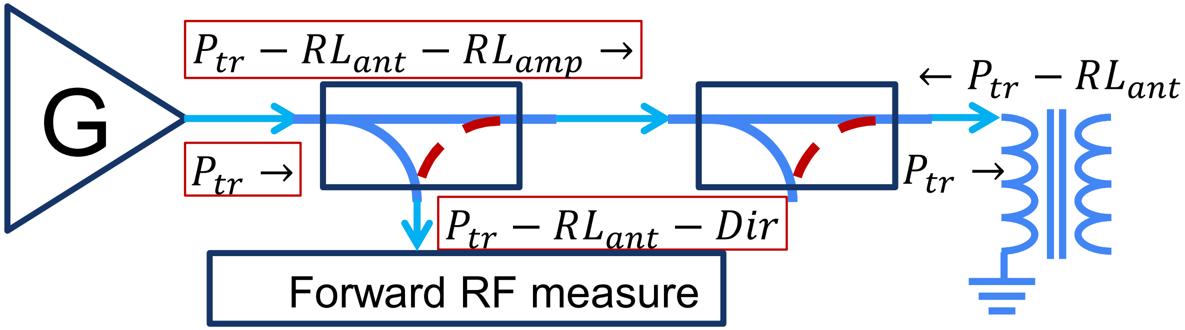
$+40°\ C, 1\ Atm$

$-60°\ C, 0.01\ Atm$

Frequency generator/Amplifier

- Try to find an integrated solution
    - Difficult to find one that fit with size and power constraints
    - Example right: 18 W
- Design from VCO/PLL/DDS/external amp components
    - Must be filtered for harmonic content
    - Amplifier power consumption : 0.5 W – 3 W
    - Frequency generation : ~ 1W
    - Must be paired with a power measurement chain

Transmission power measurement – RF chain



G

$P_{tr} - RL_{ant} - RL_{amp} \rightarrow$

$P_{tr} \rightarrow$

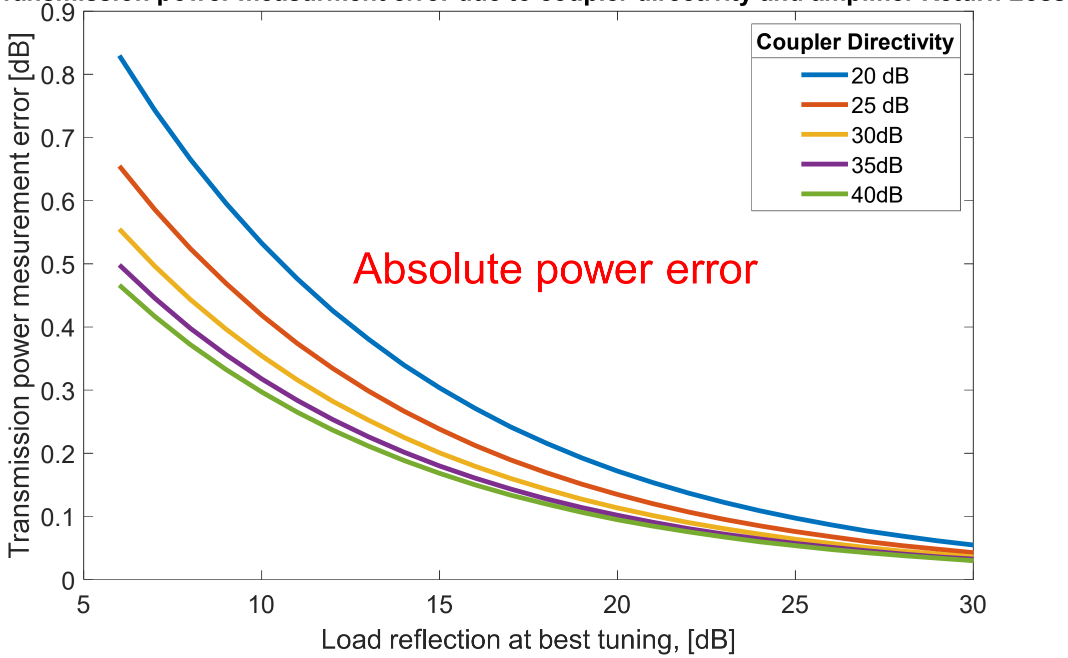
$P_{tr} - RL_{ant} - Dir$

Forward RF measure

$\leftarrow P_{tr} - RL_{ant}$

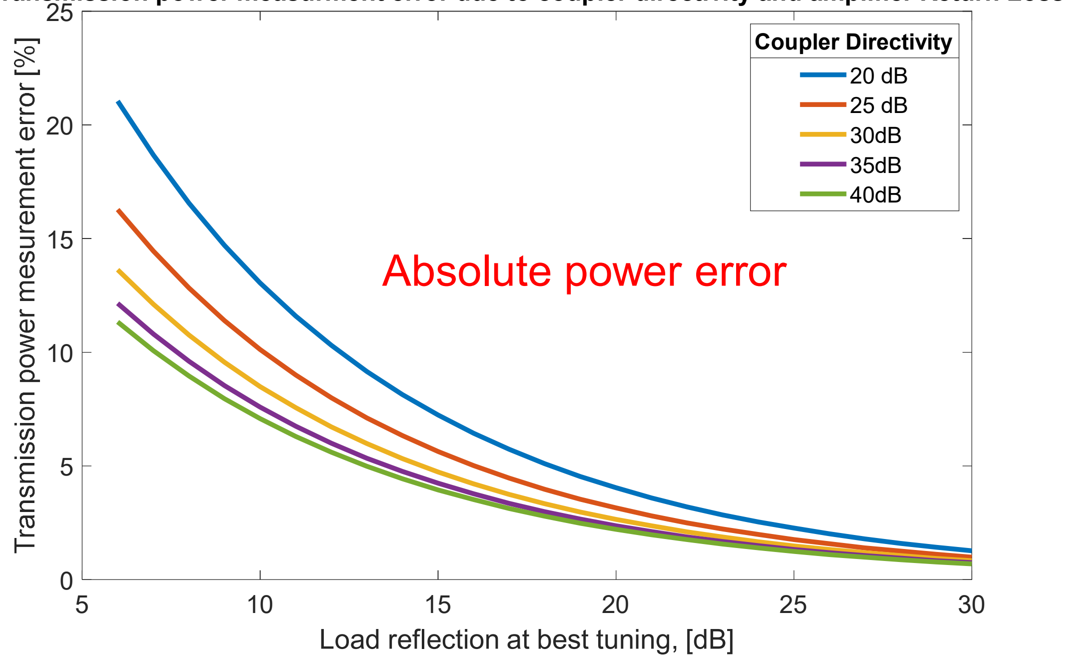
$P_{tr} \rightarrow$

Source of errors:
Directional couplers and output reflection of amplifier (presumed 20 dB) and reflection of antenna.



Transmission power measurment error due to coupler directivity and amplifier Return Loss

Absolute power error



Transmission power measurment error due to coupler directivity and amplifier Return Loss

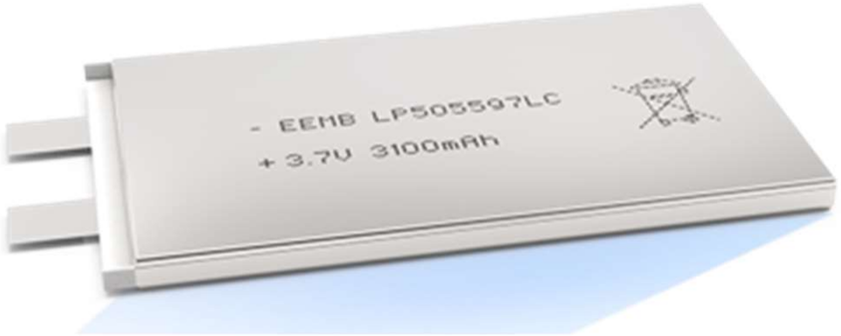
Absolute power error

Transmission power measurement – signal acquisition

- Direct sampling, possibly under sampling system or synchronous sampled
    - Can do digital filtering to ignore harmonics
    - Fast sampling ADC power consumption ~ 0.7 W
- Power detection via RF power diode
    - Measures total power including harmonics
    - Detector diode power consumption ~0.5 W

Battery and power supply

- Estimated power of RF generation and measurement chain : 5 to 10 W
- For a 4-hour flight we would need something like ~40 to 80 Wh battery (assuming half usable capacity)
- The standard 18650 type batteries exist in $-20\,°C\ -60\,°C$ discharge range and has about a 10Wh capacity and a 50 g weight.
- Other options exist than can operate down to $-40\,°C$ with similar weight/power profiles. (LiFePO4, Lithium Polymer)
- $-60\,°C$ operational temperature does not seem to exist, requiring some minimum thermal stabilisation



Thermal stabilisation of drone payload

- Top of flight is at -60 C. This is not a battery friendly temperature, ground temperature could be +40 C
- The payload would likely have to be both cooled and heated. We estimate 5 to 10 W system consumption.
- Some kind of variable heatsinking concept is needed
- Potential solution: Switchable water-cooling circuit as a function of temperature
- Switchable heat pipes are an interesting idea, but they seem to be a research concept and not available as commercial components

FHG-IPM Freiburg

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Next steps

How to go ahead

- Pre-study to define
  - Basic specifications of RF generation and measurement system
  - Flight path and associated distribution of calibration points in calibration space (angles and frequency)
  - Calibration algorithms
  - Payload architecture
  - Heating and cooling concept

- Prototype design, manufacture, assembly, integration and test (in CH)

- Flight hardware MAIT

- Test campaign on-site and evaluation

Basic specification needed to start RF and measurement system design

- Received signal strength at ground?
- Amplitude stability required of the received signal?
- Absolute emitted power measure precision?
- Relative power measure resolution?
- Permissible harmonic content in emitted signal?
- Frequency stability, absolute and relative?
- Phase noise?

Questions?

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