GINGER II: An Upgrade of the Technology Demonstrator of the Guidance and INto the Ground Exploration Radar GINGER

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ABSTRACT

In 1994 a new radar development has been initialized by the European Space Agency. RST developed the concept of a hardware sharing radar sensor combination intended for the support of planetary rover guidance by medium resolution imaging of the surface in front of the rover. At the same time, the ground penetration radar function of GINGER explores subsurface layer structures in the dry soil beneath the rover. Both operation modes make use of the Stepped Frequency Radar (SFR) principle applying the same frequency synthesizer while operating at different RF measurement frequencies. While the rover piloting functions need frequencies as high as possible, the ground penetration radar function provides best performance at low frequencies.
In order to verify the GINGER concept, an industrial team led by RST developed and manufactured a technology demonstrator instrument mainly made by components off the shelf. This system was representative for the flight unit in terms of the implementation of the individual operation modes while it was not representative concerning mass, volume and power consumption.
Finally, in 1998, the technology demonstrator was tested in environments representing Moon and Mars conditions as far as possible. While the ground penetration radar function was tested at the University of Freiberg/D and in a salt mine at Borth/D at 800 m depth, the rover guidance operation modes were tested in GEROMS, the CNES Mars and Moon rover test range.
The tests confirmed the basic potential and performance of the GINGER concept. On the other hand the tests indicated which radar parameters could be optimized.
Based on the experiences gained from the GINGER technology demonstrator instrument, RST developed a second generation technology demonstrator, GINGER II. While still relying on off the shelf components, the hardware architecture of the new instrument has been optimized, partly operating with a new set of radar parameters. Compared to the old instrument, GINGER II offers superior performance, while, at the same time, considerably reduced in mass, volume and power consumption, it gives a better indication that a later flight hardware of the complex radar system could be miniaturized to a very small volume and operate with a very low consumption.

Keywords: Planetary rover, stepped frequency radar, ground penetration radar, obstacle detection.

1. INTRODUCTION

In the frame of scientific exploration of Moon and Mars, ground penetration radar is a key element as it allows the investigation of sub-surface structures not visible by other means. Planetary rovers represent optimum platforms for these ground-based radars. The rovers, however, require very sophisticated systems for piloting and navigation. Taking into account the significant travel times for telemetry and telecommand signals between the rover and the ground stations, a certain degree of autonomy of the rover is mandatory in order to compensate for the limited support by the remote operators on Earth. The rover must be able to find a safe route in the presence of obstacles and non-traversable soils.
For the guidance functions, the radar principle was selected since it can operate without any atmosphere, under critical illumination conditions and since it is more robust than a laser. Furthermore, it could share hardware building blocks with the ground penetration radar function.
In order to verify the GINGER concept and to give inputs for optimisation, a technology demonstrator has been developed and manufactured.
In the following sections, an overview on the functions of GINGER and the antenna configuration on a rover is given. Afterwards, field test findings from the GINGER I technology demonstrator are addressed. In order to introduce the GINGER concept more in detail, the stepped frequency radar principle is discussed, and its application for GINGER II.

2. OPERATION MODES

The GINGER concept applies altogether four individual operation modes, which in case of the technology demonstrator are not required to operate simultaneously:
A **Speed Measurement Mode** based on Doppler evaluation in forward direction of the rover as well as in lateral directions provides navigation support. This mode makes use of two receive antennas at the front side of the rover and, in addition, in the case of GINGER II, one antenna on the rear side of the rover. The antenna footprints are illuminated by two transmit antennas. This mode operates in X-band. Performance goal was 1% of the actual speed.
The second mode using the X-band is the **Obstacle Detection Mode**. It applies the two forward looking receive antennas in conjunction with the corresponding X-band transmit antenna. Minimum obstacle size to be detected 20 cm. The detection distance has been selected to app. 2m.
The **Surface Penetration Mode** uses the P-band spectrum. Two downward looking antennas at the sides of the rover support the ground penetration radar operation of GINGER. Goal is a radar penetration of more than 10 m offering a range resolution of <0.2m.
Finally, an experimental **Soil Traversability Detection** Mode is implemented. It makes use of the P-band channel as well as of one X-band receiver channel; both with transmit and receive antennas illuminating the area in front of the rover. This mode is based on a phase measurement comparison between P- and X-bands. While P-band signals penetrate soft

soil, X-band signals are expected to be reflected at the surface in both cases, hard and soft soil surfaces.

3. ANTENNA CONFIGURATION

Concerning the GINGER performance the antennas play an important role. This is valid for the antenna type and characteristics and for the configuration as well. For this reason, RST acquired a rover mock-up and evaluated suitable antenna configurations. For the P-band operation two modified YAGI-antennas have been used. In X-band the receive antennas were slotted waveguide antennas with narrow patterns in the azimuth directions while the transmit antennas were represented by low gain horns.
Figure 1 demonstrates the antenna configurations for the individual operation modes.

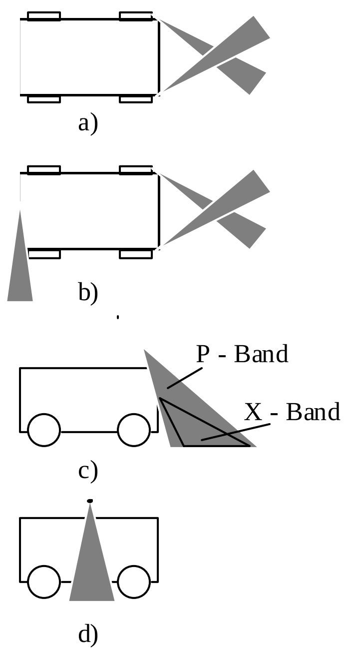

Figure 1. Antenna configurations

Figure 1a depicts the antenna configuration of GINGER I for the **speed measurement function**. For GINGER II the rear antenna (Fig. 1b) has been added.
The antenna configuration for the **obstacle detection function** is shown in Fig. 1a. Since the antennas are not looking straight ahead, when the rover drives, a "depth scanning" in front of the rover is done.
Fig 1c illustrates the antenna configuration of the **soil traversability estimation function**. The footprints of the P- and the X-band antennas should cover the same area in front of the rover.
Fig. 1d finally presents the downward looking P-band antenna beams for the **ground penetration function** at the sides of the rover.

4. GINGER I TESTING

The guidance testing was done in GEROMS, the CNES test site offering Moon and Mars soil surface conditions. The **obstacle detection function** behaved quite well. Even more reliable results would have been obtained applying higher frequencies which would not have penetrated into some of the smaller obstacles. This was known, but for budgetary reasons and the off-the-shelf availability, 10 GHz were used instead of 60 GHz planned for a spaceflight mission, however.
The performance of the **speed measurement function** was confirmed to be good. A higher frequency would have provided higher Doppler shifts and hence better accuracy, however. In addition, we learned that a third antenna, as indicated in Figure 1b, would allow to distinguish between rover turn and slipping movements. This could significantly improve the accuracy of the rover travel route reconstruction.
The **surface traversability estimation function** was a novum. The tests were very positive, again indicating that a higher frequency in the microwave channel would avoid penetration into the soil and hence be desirable.
The testing of the **ground penetration radar function** was done in a salt mine offering dry soil conditions like in Moon or Mars environment. The measurements were quite difficult since reflections from the mine tunnel walls were disturbing the results. Nevertheless, with knowledge of the geometry and comparing the results to a commercial ground penetration radar, the performance of the technology demonstrator could be confirmed.

5. THE STEPPED FREQUENCY RADAR

A. Operation Principle

In contrast to classical pulse radar systems, SFR systems operate with amplitude-continuous radar signals. The signal bandwidth being required for the desired radar resolution is generated sequentially instead of the instantaneous complete spectrum of the pulse radar case. Figure 2 illustrates the basic SFR modulation scheme. The radar transmitter sequentially provides signals stepping through the desired frequency range. Depending on the application this could be done, for instance, in linear steps as depicted in the figure. In the receiver section both, phase and amplitude measurement of the echo signals is performed. The results are fed into a data processing, the well-known IFFT (Inverse Fast Fourier Transform), for example. The outcome is a pulse corresponding to that of a pulse radar. It contains the range information of the target, while its pulse width, the radar range resolution, is related to the bandwidth of the applied radar spectrum.
The advantages of the SFR can briefly be summarized as follows: low instantaneous bandwidth, high sensitivity, high penetration depth, low sensitivity to RF-interference, low power consumption, high resolution w.r.t. measurement frequency, low output data rate, reduced wideband antenna problems. Most of the advantages are directly related to the continuous wave operation and the low instantaneous bandwidth of the SFR. The second key factor resulting from the sequential operation principle, is the unique possibility for powerful instrument calibration in both, the frequency as well as in the time domain. The influence of the overall calibration is finally reflected by the achieved radar range resolution performance.

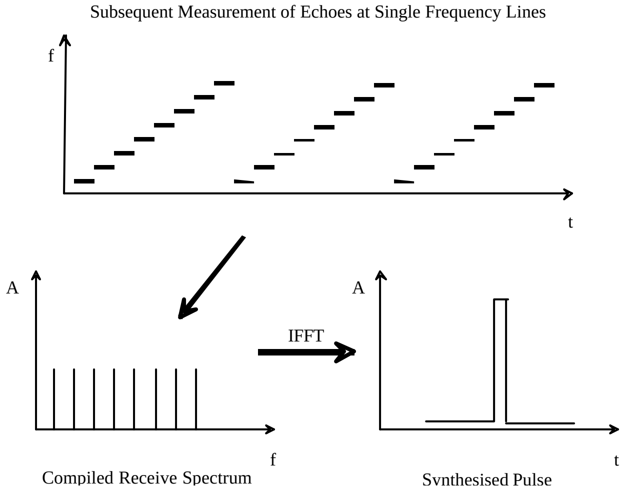

Figure 2. Basic operation scheme of a SFR

B. Conceptual Layout of a SFR Instrument

The basic block diagram of a SFR instrument is given in Figure 3. As can be seen, a PC containing the radar operation and data processing software sends commands to the radar instrument. The signals, provided by the frequency synthesizer, are amplified and routed to the transmit antenna. In addition, the transmit signals are provided to the receiver as reference signals for phase measurement. The receiver section amplifies the echo signals and performs an I/Q-detection. The amplitude and phase signals are sampled and transferred to the PC for processing.

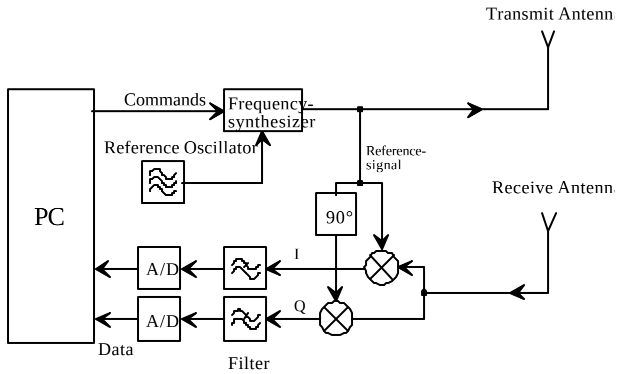

Figure 3. Basic Layout of a SFR instrument

6. THE GINGER II TECHNOLOGY DEMONSTRATOR

A. Antenna Configuration and Radar Parameters

While the tests of the first technology demonstrator confirmed the function of the individual operation modes, it turned out that the **speed measurement function** should be supported by an additional antenna (as indicated in Figure 1b) in order to be able to distinguish between rover turns and slipping movements. Therefore, a third microwave channel has been introduced in GINGER II.
The microwave channels are still operating in the 10 GHz band - for cost reasons.
The P-band channel now has an extended bandwidth. The synthesizer covers 0.5 to 1 GHz. The useable bandwidth is mainly limited by the antennas. The microwave channels benefit from the increased bandwidth (and resolution) as well.
The number of frequency lines has been increased from 32 to 256. This extends the radar reflectivity contrast, which can be handled by the instrument.
The measurement speed has been increased to 4 frequency sweeps per second which now matches the practical needs very well.

B. Hardware Concept

As mentioned previously, GINGER represents a combination of several radar functions. These individual operation modes can be provided by a building block sharing radar hardware. The basic scheme is depicted in Figure 4. Key element is the stepped frequency synthesizer applying DDS (Direct Digital Synthesis) technology. It operates from 0.5 to 1 GHz and is used for the P-band and for the X-band channels as well. Commands sent by the laptop PC, which runs the radar operation and data processing software, are translated by a micro-controller into hardware settings for the synthesizer and the receivers.
Figure 4 illustrates that the synthesizer signals are directly used in P-band while in X-band up-conversion and sideband filtering is performed. The synthesizer provides the reference signals for I/Q-detection of the radar returns for all receivers, whereas additional downconversion takes place in the case of the X-band receivers. The detected signals are sampled and finally routed to the laptop PC for data evaluation and storage.

From the experiences obtained with the technology demonstrator GINGER I, a "streamlining" of the radar hardware and an optimization of the hardware architecture could be derived. As a consequence, GINGER II easily fulfils the specification for mass, volume and power consumption:

Mass	3.3 kg
Dimensions	15 cm x 11 cm x 27 cm
Power consumption	4 - 8.5 W (depending on activated operation modes)

Figure 5 presents a photograph of the GINGER II technology demonstrator.

C. Instrument Calibration

From the first technology demonstrator we learned the crucial role of proper radar instrument calibration which finally brings the radar performance of the SFR close to theory.
The objectives of the calibration mainly are to improve the radar resolution and to remove "ghost images" from the radargram. Both is achieved by compensating for a variety of hardware imperfections as they are:

Amplitude and phase nonlinearities
I/Q channel imbalances in the detector section
DC-offsets of the phase detectors
Gain and phase imperfections of the antennas

Once the calibration coefficients are determined, they can be stored in the computer and applied on the acquired raw data during radar operation.

7. FURTHER DEVELOPMENTS AT RST

The enormous potential of the SFR, which was revealed during the GINGER evaluations and operation, finally led to further developments of this technology. In order to study a variety of radar scenarios, at RST a very versatile SFR instrument, called SUSI (Stepped frequency Ultra-wideband Synthetic aperture radar Imager) has been designed covering a frequency range from 1MHz to 8GHz and offering altogether 4 receivers. Adjustable parameters are centre frequency, radar bandwidth, number of frequency lines, dwell time per frequency line, number of samples per frequency line. Being a forerunner of a next generation of radar systems, this instrument has widely been used. From the experiences made, a very compact new device operating in the frequency range from 2-6GHz and especially dedicated to humanitarian demining applications has been derived. RST applies a similar radar technology, using several receiver channels however, for the detection of cracks in underground tunnels of the mining industry.

8. CONCLUSIONS

The GINGER I technology demonstrator was a valuable study concerning the optimization of a planetary rover-based SFR instrument and the potential of the SFR principle for various other applications.

The GINGER II has been created as an upgrade of the first technology demonstrator. While it still applies components off the shelf as far as possible, it offers improved radar performance due to optimized operation parameters, state-of-the-art technology and an optimized hardware architecture as well as a powerful instrument calibration. Reduced size, mass and power consumption give a brief impression of the potential in miniaturisation and performance of a dedicated instrument built applying space hardware design and construction techniques.

9. REFERENCES

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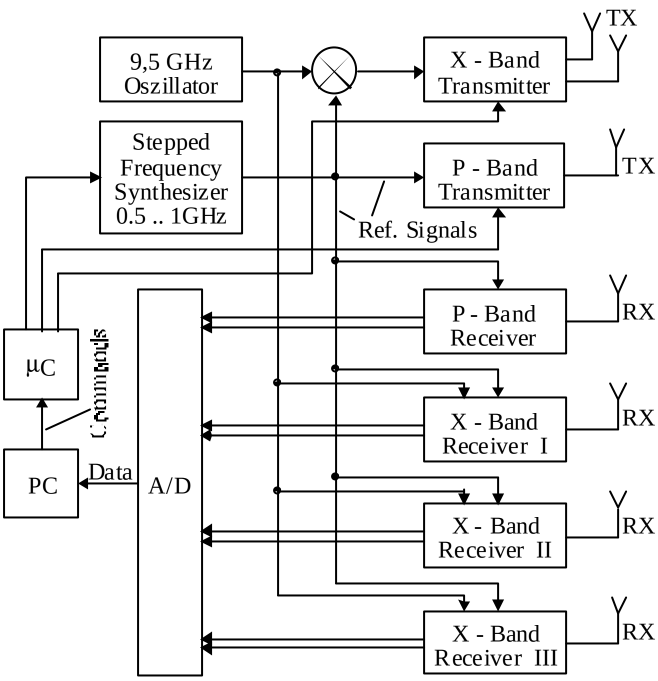

Figure 4. Basic hardware architecture of GINGER II

Figure 5. Photo of the GINGER II hardware in comparison to a cigarette box.