TITLE: UAV Data-Links: Tasks, Types, Technologies and Examples

UAV Data-Links: Tasks, Types, Technologies and Examples

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Introduction

This paper provides an overview of Data-Links for UAVs. Based on the functions, which have to be performed in different UAV missions, requirements for data-links are identified.

After highlighting the basic variants of data-links and their general advantages and disadvantages a detailed discussion of some important design aspects is provided.

Some real-world examples of data-links show how theory has been put to use, namely

- Global Hawk SATCOM Data-Link as an example for an off-the-shelf solution.
- HF Data-Link for Mücke UAV System as an example for the adaptation of MOTS hardware to a small UAV.
- The BREVEL Microwave DATA-Link as an example for a solution to a specific requirement. The BREVEL Data-Link is one of the most advanced solutions available today. It was developed jointly between DaimlerChrysler Aerospace AG and MATRA SYSTEMS & Information until 1998 and is expected to go into production in Germany in 1999.

DaimlerChrysler Aerospace (Dasa) History on Data-Links (viewgraphs 2 to 4)

Data-Link activities in Dasa have started in the former AEG company in Ulm, which was later-on merged with Dornier, Messerschmitt-Bölkow-Blohm, MTU and others to form Daimler-Benz Aerospace (now DaimlerChrysler Aerospace, Dasa) which now also comprises the former Defense Activities of SIEMENS. With revenues of 17 Billion DM, Dasa makes up about 7 % of the business in the DaimlerChrysler Group. Data-Link activities of Dasa are handled within the Defense and Civil Systems Division, which has its premises in Ulm, Munich and Friedrichshafen.
Data-Link Activities for missile and UAV systems started in the 1970s with the command link for the ROLAND Air Defense Missile System.
Currently numerous data-link activities are in the feasibility or DemVal phase. Dasa Ulm (VMFW3) was the leader of a co-operation with MATRA Systems & Information for development of the Microwave data-link for the BREVEL UAV system. An HF data-link based largely on MOTS hardware is currently in development in Ulm for the German Mücke Jamming UAV System.

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UAV DATA-LINK TASKS AND REQUIREMENTS

(viewgraphs 5 to 9)

Unmanned Air Vehicles have enjoyed growing importance during the last two decades.
UAV Systems today are used to perform a multitude of missions both military and civilian. Typical UAV missions in the military field comprise

- Reconnaissance
- Targeting and Fire Control
- Attack
- Suppression of Enemy Air Defence (SEAD)
- COMINT and ELINT
- Jamming

Many of these missions require instantaneous exchange of information between the UAV and a ground-control station. This information exchange is performed by a DATA-LINK.

Depending on the particular mission one or more of the following functions have to be performed, which involve a data-link.

- The flight-path of the UAV has to be controlled from the ground, the platform of an on-board Sensor is to be directed, or an on-board equipment, e.g. a jammer, has to be activated or de-activated. All of these actions require a communications channel from the ground to the UAV.
  This channel is called TELECOMMAND UPLINK (TC) and can usually be of low capacity.
- The status of the UAV itself or of an on-board equipment has to be monitored in the ground control station. Information from on-board sensors, which only deliver a limited amount of data, e.g. altimeter or inertial measurement unit, may also have to be transferred.
  These data from the UAV to ground can be transmitted through a low capacity channel, which we call TELEMETRY DOWNLINK (TM).
- In missions like surveillance or target search, fire control or battle damage assessment a large amount of data from on-board SAR radars or electro-optic sensors has to be transmitted from the UAV to a ground control station. This amount of data requires a channel with very high data rate. This channel is called TELEVISION DOWNLINK (TV).
- In case of UAV missions, which are concerned with fire-control of weapon-systems, ground-targets have to be located by the UAV with a precision, that is compatible with CEP or footprint of the weapon. Consequently the location of the UAV has to be known with of least the same precision. Although this is principally possible with GPS using the military P/Y code, jamming of GPS in a tactical UAV is relatively easy in a battlefield scenario. It is especially likely if the enemy knows that the UAV presents a high threat. Therefore this localization function should be integrated into the data-link if sufficient accuracy can be achieved.

Data-Link Range, depending on UAV class and task can be from 20 km to several hundred kilome-ters. Data rates can vary from around 100 bit/s for control data to over 100 Mbit/s for uncompressed video.
Data-Links employ communication modes of different complexity:

- Simplex, so that the sender has no knowledge of correct reception of his transmission
- semi-duplex, allowing confirmation of small packets so that errors can be corrected with minimum delay
- full duplex, which puts both sides in continuos communication with each other and allows a maximum degree of error-free information transfer and thus reliability.

The type of link mode also determines to a large extent the degree of ECM susceptibility, which is of importance for military 'UAV missions.

Data-Link equipment has to be suited to the space and environmental conditions found in the UAV and must not interfere with other systems onboard the UAV.
For tactical UAVs the data-link equipment must normally not exceed 20 kg in mass and 200 W of power consumption. Less is always preferred.
Data-Link equipment in the ground station, depending on the type of UAV system may be subject to the same or even more demanding conditions, than in the UAV. This is especially true for tactical UAV systems, which require a highly mobile ground station.

In addition to the environmental conditions for the Air Data Terminal and the Ground Data Terminal there are also environmental conditions for the communications channel itself.

Depending on frequency range the commu-nications channel features self implied charac-teristics like

- Line of sight conditions
- Attenuation imposed by range, atmosphere and weather
- Disturbances like multipath effects, noise and
- Ionospheric disturbances and daily variations resulting from solar activity.

In addition to these natural influences, the communications channel is subject to intentional influences by various types of jammers like

- noise jammers, both wide and narrow band
- pulse jammers
- spot jammers
- repeater jammers and
- intelligent jammers.

A low probability of intercept of the data-link reduces the risk of jamming.

These effects of the communications channel have to be taken into account in data-link design based on the requirements and criticity of the UAV mission.

UAV DATA-LINK TYPES AND GENERAL CHARACTERISTICS

(viewgraphs 10 to 17)

From the users point of view the main selection criteria/requirements are usually

- Range and
- Data-Rate.

In addition to that

- Link Protection (Jamming Resistance)

is an important requirement.

When looked at by the designer, these requirements have to be translated into

- operating frequency
- bandwidth
- antenna characteristics
- signal processing.

These criteria are used in this chapter to identify some basic data-link variants and to characterize them by their main characteristics.

Analog Versus Digital (viewgraph 11)

A powerful reservoir of signal processing techniques is available to the designer to provide a high degree of link protection. These techniques will be dealt with in more detail in the next chapter.

For the purpose of general classification in this chapter it is of importance that most of these signal processing techniques require a **digital** data-link as compared to an **analog** one.

While in an analog link signal are transmitted by traditional modulation techniques such as

- amplitude modulation (AM Radio)
- frequency modulation (FM Radio)

which transform all characteristics of the original signal into the RF wave form, a digital link takes a different approach. The original signal is first digitized; the resulting data stream is used to modulate the carrier by means of

- Phase Shift Keying (PSK) or
- Frequency Shift Keying (FSK)
- Amplitude Shift Keying (ASK).

Thus the RF signal only varies between two conditions at any time.

A digital link allows to manipulate the signal in order to create redundancy and jam resistance to a much larger extent than possible in an analog link. While analog links are still widely used in UAV systems today digital links are clearly going to become the future standard.

Bandwidth (viewgraph 12)

Bandwidth is the resource, which is required to transfer a certain amount of information in a given time-segment. In addition most of the signal-processing techniques used in digital links in order to provide jamming resistance are bandwidth-consumers on top.

In image- and TV-transmission, compression techniques can be applied to the signal from the camera to limit the amount of information and thus the bandwidth requirement. MPEG and JPEG are common compression techniques used in computing devices for the consumer market.

Generally speaking, the data-rate of a digital-link using BPSK (expressed in bit/s) is roughly identical to the required bandwidth (expressed in Hz).

In a radio frequency system, many components, e.g. antennas and amplifiers, can only cover a certain percentage of their operating frequency before their performance deteriorates substantially. For this reason the usable bandwidth can generally not exceed ~ 3 % of the operating frequency.

Operating Frequency (viewgraph 13)

When selecting the operating frequency of a data link the following aspects have to be taken into account

- propagation characteristics
- achievable power
- achievable antenna characteristics
- available bandwidth.

The frequency spectrum from HF to microwave can generally be characterized as follows:

- HF frequencies (1-30 MHz) propagate by ground-wave, sky-wave and line-of-sight and thus allow coverage of long distances.

  However, usable bandwidth is small and antennas with gain are gigantic in terms of UAV dimensions.

- VHF/UHF frequencies (30 MHz to 1 GHz) can cover substantial distances through propagation by diffraction in the lower part of the spectrum.

  However, power levels for diffraction propagation are too high to be feasible in small UAVs and antennas with gain are still too big.

- The Microwave Spectrum (1 GHz to 100 GHz) is of main interest to UAV applications, as it offers the possibility to use high bandwidth for picture transmission. Antennas of high gain can be built at dimensions, which can be accommodated in a UAV.

  The drawback of the microwave spectrum is that propagation is limited to line-of-sight and power levels are limited to a few watts unless high voltage tube transmitters are used.

Based on the above the general characteristics for three basic variants of UAV links are described.

Short-Wave (HF) Data-Links (viewgraph 14)

Due to sky-wave propagation by reflection at the earth's ionosphere short-wave links can cover up to about 500 km (non-line-of-sight) at power levels and antenna sizes feasible in a UAV installation.

Due to bandwidth limitations to ~ 100 kHz HF data-links can generally not be used for TV picture transmission. An exception is the transfer of still (frozen) TV images, which can be transmitted by so-called slow-scan techniques (1 picture typically takes more than 10 seconds). Due to variations in propagation characteristics the usable part of the HF spectrum for UAVs is limited to the range of 2-12 MHz.

Microwave Data-Links (viewgraph 15)

Microwave Data-Links are clearly the workhorse in UAV applications. They are characterized by benefits like

- large available bandwidth which allows transmission of live-video.
  The following bands are used for to data-link applications
  - Ku-Band (15 GHz)
  - X-Band (10 GHz)
  - C-Band (5 GHz)
  - L-/S-Band (1-2 GHz)
- High Bandwidth together with high gain antennas, which can be installed in UAVs due to their relatively small dimensions, allow to make microwave links jam-resistant.

The only disadvantage in microwave links is that they depend on line-of-sight propagation, which limits their coverage to < 100 to 300 km depending on UAV altitude and terrain.

If the UAV mission cannot tolerate this limitation an airborne relays has to be used. This can either be an aircraft, another UAV or a satellite.

Satellite Data-Links (viewgraph 16)

Satellite Data-Links are a special case of a microwave data-link to overcome the range limitation normally imposed by the line-of-sight requirement.

Depending on the number and orbit of the satellites used satellite links can give a UAV world-wide coverage.

Limitations for the use of satellite links are

- Availability of military communication satellites
- Cost and availability of commercial wide-band satellite capacity
- The long distance of the UAV to satellite requires extremely high-gain directional antennas, which cannot be installed in tactical small UAVs.

The use of wide-band satellite data-links today is mainly limited to High-Altitude, Long-Endurance (HALE) UAVs in countries, which can secure satellite transmission capacity.

For tactical UAVs satellite links are not (yet) an alternative today.

UAV DATA-LINK DESIGN ASPECTS AND TECHNIQUES

(viewgraphs 17 to 39)

The key factors in data-link design are the requirements concerning

- Jamming-Resistance
- Range
- Data-Rate

In today's battlefield environment Jamming-Resistance and Low-Probability-of-Intercept of the data-link are extremely important factors for mission success.

These requirements have to be fulfilled under the constraints imposed by the Air Vehicle, which are mostly more stringent than the constraints to the Ground Data Terminal.

Constraints for Air-Vehicle Integration (viewgraph 18)

The air-vehicle imposes limitations to the airborne data link terminal in terms of :

- weight,
- size,
- power supply,
- thermal dissipation,
- antenna.

These limitations influence some key design features of the data link like:

- **Transmitter power** is limited by power-supply of the A/V, allowable thermal dissipation, mass and size.
- **Antenna type and gain** are limited by the antenna mass, size and position, which is allowed by the A/V under aerodynamic considerations.
- **Frequency band** has to be chosen based on the antenna size and transmitter-power, which allows to satisfy the link budget under jamming conditions.

Link Budget

The link budget is the output of the link analysis. It consists of the calculations and tabulation of the useful signal power and the interfering noise power available at the receiver.

Link Protection and Quality

In the case of military applications, one of the specific constraints is to provide the quality required for the communication under threat, generally in the presence of hostile jamming, which represents also additional sources of noise in the link.

Typical protection methods are :

- directional antennas,

- robustness of the modulation

- spread spectrum techniques

- forward error correction.

The above design considerations will finally lead to certain degrees of complexity, flexibility and cost, which together with the data-link performances have to be subject to trade-offs to come to a well-balanced, optimized and cost-effective solution.

Definition of Link Quality and Link Budget Examples

(viewgraphs 19 to 27)

Quality of a communications link in general terms is determined by

- Radiated power from the transmitter and the
- Minimum signal power at the receiver, required for communication.

In these terms link quality is the maximum allowable path loss between transmitter and receiver if jamming and other interference is not considered.

The major tool for analysis of link quality is the link budget.

The link budget is a balance of gains and losses, e.g.

- transmitter power (on board power is limited)
- antenna gain (size is limited by UAV shape and aerodynamics)
- processing gain

- propagation losses due to atmospheric attenuation and earth surface effects depending on frequency band (UAV mission area)
- Losses due to real-life imperfections in the signal amplification and processing circuit.
- engineering implementation inside the UAV.

Radiated power P_0 from the transmitter expressed in dBm leads to a decreasing power density p depending on the distance d to the receiver. In free space this power density can be expressed as

$$p = \frac{P_o}{4\pi d^2}$$

From the capture area (aperture) of the receiving antenna (A) and wavelength (λ) the receivers antenna gain G in dB can be calculated as

$$G = 10 \log \left(\frac{4\pi A}{\lambda^2} \right)$$

The received signal power S expressed in dB above 1 mW (dBm)is thus

$$S = P_0 + G - 10 \ \log \left(\frac{4\pi d}{\lambda} \right)^2 .$$

This received signal power has to compete with self-generated thermal noise in the receiver, which results from molecular movement in the receivers components. This noise is bandwidth dependent, so that it is more significant for signals with high data-rate r.

The noise power N in dBm can be calculated as

$$N = -174 \, dBm + 10 \log (r) .$$

The result of S and N is the so-called signal to noise ratio (SNR)

$$\text{SNR} = P_0 + G - 10 \log \left(\frac{4\pi d}{\lambda} \right)^2 + 174 \text{ dBm} - 10 \log (r).$$

The Signal to Noise Ratio allows an initial rough judgement of data-link performance.

For standard modulation techniques an SNR of ~ 10 dB will allow error free communication. Special modulation techniques allow communication at considerably lower SNRs.

However, with this initial SNR calculation one has to keep in mind that losses from

- cables, radomes, switches
- weather
- multipath effects and
- jamming

have to be taken into account additionally.

On HF the thermal noise generated in the receiver is generally of no significance. The limiting factor here is atmospheric noise, which depends on time of day and frequency (viewgraph 23).

Some examples of path losses in typical microwave bands show that the additional path loss at high frequencies (e.g. 15 GHz) when compared to low microwave frequencies (e.g. 2 GHz) is more than compensated by the antenna gains in the UAV at 15 GHz. This gain at 15 GHz has the added advantage that it comes along with a narrow beam-width < 10°, which can be put to use for anti-jamming purposes. These narrow beam antennas on the other hand result in some additional complexity for antenna control as the antenna has to remain pointed to the ground station during all UAV manoeuvres (viewgraph 24).

From a simple example of a link budget for a TV data-link in Ku-band it can be seen, that the antenna gains, which are possible at this frequency, allow communication over a distance of 100 km in adverse weather with a transmitter power of less than 1 watt.

The corresponding power for omni-directional antennas would be 1.2 MW (1,2000,000 W) instead. Transmitters of this power level are neither feasible in Ku-band nor could they be packaged in an airborne platform (viewgraph 25).

Although significant distances can be covered at microwave frequencies from a link budget point of view it has to be always kept in mind that the line of sight condition has to be satisfied in the first place. Although ranges of 180 km can be covered with UAV altitudes of as low as 1500 m even slightly hilly terrain can reduce this range to less than 100 km at the same flight altitude (viewgraphs 26, 27).

Jamming Resistance (viewgraph 28)

In addition to propagation effects, jamming is another important influence on data-link quality.

In today's battlefield environment jamming-Resistance and Low-Probability of Intercept of the data-link are extremely important factors in UAV missions success.

In a jamming environment the transmitted signal may well have to compete with jamming-signals, which are 10.000 times or 40 dB stronger.

Some anti-jamming features will be looked at in more detail in the following:

- Narrow Beam Antennas
- Direct Sequence Spread Spectrum
- Frequency Hopping Spread Spectrum
- Channel Coding.

Narrow Beam Antennas (viewgraphs 29 to 31)

Jammers, which do not enter directly into the main lobe of the antenna, can be attenuated substantially. When received via sidelobes jammers are attenuated by ca. 20 dB for the first sidelobe and by an even greater amount for the far side-lobes. Antennas designed for particularly low side-lobes reach an attenuation of > 40 dB for the far side-lobes. Thus the areas, which can be protected by a jammer, can be reduced substantially.

Generally the wide-band TV channel from the UAV to ground is the most vulnerable part of the link; consequently the Ground Data Terminal should be equipped with the narrowest antennas in order to make the receiver as jamming-proof as possible.

For a given size of the antenna the highest frequency band will allow the narrowest antenna beam.

For a given transmit power and volume in ADT and GDT the gain and sidelobe suppression advantage of Ku-Band antennas over S-Band antennas will result in a jam-resistant Ku-Band range up to 100 km while S-Band and C-Band communication are totally lost and X-Band range is reduced to 50 km.

Signal Processing for Anti-Jamming (viewgraph 32)

A typical digital data-link can be designed for anti-jamming performance in the following way: After Channel-Coding of the source data stream, the coded data stream is multiplied by a higher rate spreading code. The resulting high-rate data stream is used to modulate an intermediate-frequency microwave signal by a digital modula-tion, e.g. BPSK. This results in a so-called Direct-Sequence Spread Spectrum Signal at the interme-diate frequency, which is mixed to a set of trans-mitting frequencies in the band of operation by means of a Frequency Hopping Synthesizer which selects one of the frequencies at a time.

The different steps of signal processing shall now be looked at in a bit more detail below.

Channel Coding (viewgraphs 33, 34)

This technique serves the purpose of structuring the data stream and adding redundancy, which allows to

- identify corrupted parts of the message after reception
- correct the errors by making use of the redundancy introduced in the transmitted data stream.

A special feature in channel coding is the interleaving of information. By this technique a block of the transmitted signal, which can be corrupted e.g. by a pulse jammer, is transformed into many small parts of words in the coded data stream. These small parts, when corrupted, can still be detected and corrected by the outer coding.

Direct Sequence Spread Spectrum (viewgraphs 35 to 37)

Another efficient way to minimise interference by jamming signals is to spread the power spectrum of the signal before transmission and to de-spread it after reception. This leads to the effect, that the bandwidth of the transmission is much larger than the minimum bandwidth, which would normally be required.

In DSSS each Bit of the original Signal is multiplied with a specific DS Code. This leads to a pseudo-random DSSS Signal, which is used to modulate the Radio Frequency Signal by BPSK (Phase Shift Modulation). After reception and demodulation the signal is correlated with the same DSSS Code used in the transmitter. Unless a jammer has knowledge of the DS code and thus uses exactly the same waveform and synchronization (which is very unlikely) it is substantially attenuated by DSSS. The same is true for unintentional interference effects in the communications channel.
The DSSS code can be selected from a data base of codes and loaded into the data-link equipment prior to the mission. The probability of a jammer using the data-link DSSS code is therefore mini-mal.

Frequency Hopping Spread Spectrum (viewgraph 38)

In the case of an extremely strong Noise Jammer further anti-jamming features are useful in addition to DSSS. By Frequency Hopping Spread Spectrum (FHSS) the carrier frequency of the transmitter

signal is changed pseudo-randomly according to the FHSS code between a given number of frequencies. By FHSS the effectiveness of a jammer, which can overcome DSSS is reduced proportionally to the number of frequencies used, so that the remaining interference effects can be corrected by channel-coding.
As for the DSSS code the FHSS code can be selected from a database and loaded into the data-link equipment prior to the mission.

Data Link Design Summary (viewgraph 39)

As a consequence of the previous discussions the following design features should be selected for a wide band microwave data-link.

- Use of Ku-Band

  In addition to the fact that this band is recommended for UAV use by NATO the Ku-Band has the following advantages

  - allows very small antennas at sizes, which can still be accommodated in a tactical UAV
  - a wide frequency range is allocated for data-links, which allows very wide-band transmission. Very high bandwidth together with frequency hopping and direct sequence spread spectrum is very difficult to implement in the other microwave bands due to congestion.

- Directional antennas should be used to limit transmitter power and to make the link jam-resistant and difficult to intercept. Additionally narrow-beam antennas can reduce multi-path effects and allow angle-tracking of the UAV.

- Direct Sequence Spread Spectrum (DSSS) improves the jamming resistance of the link and allows a precise measurement of the distance to the UAV.

- Frequency Hopping Spread Spectrum further improves the links jamming resistance and is a very effective way to minimize the influence of multi-path effects.

- Channel Coding allows to minimize the Bit Error Rate (BER) for a given signal to noise ratio and allows to correct errors. Interleaving is an effective counter-measure against pulse jammers.

UAV DATA-LINK EXAMPLES

UAV Satellite Link – Example: Global Hawk (viewgraphs 41, 42)

Global Hawk is a high-altitude, long endurance UAV equipped with SAR and EO sensors. With a range of ca. 25,000, a maximum altitude of 20,000 m and a mission time of up to 40 h it is a truly impressive UAV.

The UAV has a size, which comes close to manned aircraft of the business-jet class. This size allows some flexibility in the selection of on-board equipment.

As a result military off-the-shelf (MOTS) equipment could to be used for the SATCOM Data-Link. By combining a number of standard 1.5 MBit/s SATCOM channels an overall data-rate in excess of 45 MBit/s can be achieved.

This size of aircraft allows to accommodate the very sizeable antenna, which is necessary for this type of SATCOM Link. With an antenna diameter of 1.25 m and a volume of ca. 1 m^3 the space taken up by the antenna unit would be sufficient to accommodate a complete tactical UAV.

To keep the pencil beam of this antenna (~ 1.5°) focussed on the satellite high precision antenna control and a very accurate long term measurement of the UAV's orientation in space are necessary.

In a UAV of this class the choice of SATCOM is a feasible way to avoid many of the problems that tactical UAVs are facing.

HF UAV Data-Link – Example: Mücke Jamming UAV System (viewgraphs 43 to 46)

The Mücke UAV System is used for jamming of enemy communication systems at VHF and above using jamming equipment developed by Dasa in Ulm. As a consequence a microwave Data-Link cannot be used for EMI reasons.

The tasks of the Data-Link in the Mücke System are confined to data transfer for Jammer Control, Status and Position Request and Reporting and updating of the Mission Plan.

This results in an overall data rate of ~ 1 kb/s, which can well be accommodated by an HF Link.

The requirements to the link allow to base it on military-of-the-shelf equipment (MOTS). In this case components of the HRU 7000 system, developed by Dasa in Ulm for long-range reconnaissance forces of the army, were used:

- The HRU 7000 digital transceiver, which covers the HF spectrum with an output power of 30 watt. This transceiver also includes a link processor to control frequency hopping and co-ordination of the semi-duplex communication with its counter part. A digital HF modem is also included.
- The ATU 7000 Antenna Tuning Unit allows to match whip antennas, random wires and dipoles over the whole HF spectrum.

As the Mücke UAV is a relatively small A/V with a wingspan of ca. 3.5 m and a length of ca. 2.5 m integration of an efficient HF antenna is a challenge. Full-size dipole antennas covering 2 MHz to 12 MHz would have a length between 80 m or ca. 12 m respectively.

A shortened horizontal dipole antenna with capacitive loading was integrated into the wing-edge of the UAV and is matched by a modified ATU 7000 to the HRU 7000. Ranges of more than 400 km can be achieved with this configuration

As can be seen from this example even small UAVs can be equipped with an HF-Link for long-range non-line-of-sight communication using COTS hardware if low data rate can be tolerated.

Microwave UAV Data-Link – Example: BREVEL Reconnaissance UAV System (viewgraphs 47 to 59)

A high-sophisticated data-link has been developed in a co-operation of **DaimlerChrysler Aerospace** and **MATRA Systemes & Information** for the **BREVEL RECONNAISSANCE UAV System**. This system has been jointly developed by Germany and France between 1992 and 1998.
The BREVEL System is a highly mobile UAV System for deployment in close proximity to the battlefield. Consequently the exposure to ECM is very high and the data link equipment has to withstand extreme environmental conditions.

BREVEL Operational Tasks (viewgraph 48)

The BREVEL System is used for reconnaissance missions over the battlefield area using an IR camera. In addition to that targets detected in the footprint of the UAV sensor shall be located with a precision, that allows engagement of that target by weapons like MLRS or SMArt 155 to their maximum engagement range.

Design Drivers for the BREVEL Data-Link (viewgraph 49)

Concerning the data-link this mission requires

- an extremely high resistance to jamming
- low detectability
- the ability to correct errors
- flexibility in the anti-jamming characteristics from mission to mission
- precise localization of the UAV
- survivability to battlefield conditions like NEMP

BREVEL Data-Link Design Choices (viewgraph 50)

For the above requirements a digital Data Link is the logic choice.

Due to the digital nature of the Radio Frequency signals a digital link allows powerful information- and signal processing, that is not possible to the same extent with the analog data-links still deployed in most UAV systems today.

A digital link is the basis, on which the most performant spread spectrum techniques and error correction techniques can be applied. Together with an uplink and a downlink, which exist at the same time on different frequencies, a so-called full-duplex solution the anti-jamming performance is further improved and propagation delay between UAV and ground can be measured very precisely.

The link becomes even less vulnerable through the use of highly directional antennas, which also improve the link budget and are the basis for tracking of the UAV and measurement of the UAVs direction.

Localization Function (viewgraph 51)

The localization function is a special design feature of the BREVEL Data-Link, which allows to determine A/V localization with sufficient accuracy for engagement of ground targets in the footprint of the imaging sensor. This makes the system independent of the GPS P/Y code.
The localization function requires knowledge of AV direction and AV slant range relative to the Data Link Vehicle (DLV) and the height of the AV. Together with accurate knowledge of the DLV location this information allows precise location of the Air Vehicle.

In the ground data terminal the monopulse principle, which is widely used in radar systems, is used for direction measurement.

For monopulse measurement special circuitry is used to generate two antenna diagrams, one of which has a maximum in the boresight of the antenna, while the other diagram has a sharp notch in this direction.

This feature allows to precisely determine the direction to the Air Vehicle within the beam of the antenna of the GDT. Together with precision mechanics, which have to even compensate for bending of the mast in the wind, the direction in a reference grid is determined.

The slant range to the Air Vehicle can be calculated from the propagation delay, which can be very accurately measured from the code synchronisation in transmitter and receiver.

The height above sea level is measured in the ADT and transmitted via the data link.

In addition to localization, the monopulse principle is used to track the Air Vehicle from the GDT so that a very narrow-beam antenna can be used, which reduces the vulnerability to jamming and relaxes the need for transmitter power.

BREVEL Data-Link Technology (viewgraphs 52, 53)

The Data Link is made up of an Airborne Data Terminal (ADT), which is located in the BREVEL Air Vehicle, and a Ground Data Terminal (GDT) fitted on the mast of the Data Link Vehicle. These equipments will be described in more detail later.

The following design features have been applied to both equipments.

- high modularity to satisfy the maintainability and also to facilitate the integration between antenna, microwave- and base-band technology.
- identical technology in the two equipments to harmonize the dual functions and also to simplify the spare parts.
- use of identical subunits in ADT and GDT wherever possible.
- ASIC technology for base-band processing
- use of solid state microwave power amplifiers
- highly compact synthesizers
- use of modular microchip thin films microwave circuits
- use of chip carriers components on collaminated Printed Circuit Boards for signal processing circuits
- Status monitoring.

Key Design Features

The Ku frequency-band has been chosen for operation of the BREVEL Data-Link, as it allows directional antennas of reasonable size to provide an excellent compromise between range and anti-jamming performance.

Unless extreme jamming and weather conditions occur a range in excess of 150 km is achieved with this link.

This range is determined by the television channel, which is currently dimensioned for a data-rate of 10 Mb/s. A substantially higher range is possible for Telecommand and Telemetry channels.

The BREVEL Data-Link is designed to provide

- a high level of protection associated with very low level of detectability
- high accuracy of UAV localization under severe jamming conditions
- compatibility with severe environmental conditions including Nuclear Electro-magnetic Pulse (NEMP)

The very high degree of performance is achieved by means of specific techniques:

- combined Frequency Hopping (FHSS) and Direct Sequence Spread Spectrum (DSSS) modulation working full duplex for: Telecommand, Telemetry and Tele-vision.
- Non-coherent detection providing higher reliability, efficiency and robustness against sporadic signals compared to straight forward designs based on carrier phase recovery.
- detection and correction codes (FEC) optimized on both random errors and message reconstruction.
- High-speed synchronization process for shorter acquisition and reacquisition time due to specific Surface Acoustic Wave (SAW) matched filters.
- possibility of self adaptive level of transmitted power to minimize detectability and to take the most advantage of the transmitter power available on board.

- highly directional antennas with high gain, low side lobes and accurate motorization.
- design of the most complex functions at base-band level providing maximum flexibility for possible adjustments and future growth potential.
- calibration free ranging technique
- high ranging accuracy thanks to short time DSSS chip.
- unbiased monopulse processing for high azimuth localization accuracy under jamming conditions
- high dynamic range of the receiver associated with intelligent automatic gain control (AGC) strategy to cope with the high level of jamming signals.
- sophisticated and very accurate built in test (BIT) designed to diagnose Line Replaceable Units (LRU) without any specific operational maintenance test equipment.
- high scale integration for devices (ASICs) offering the best compromise between:
  - volume/weight
  - power consumption/temperature
  - processing power/complexity
  - availability/reliability.

BREVEL Air Vehicle (viewgraph 54)

The Airborne Data Terminal is fitted in the BREVEL Air Vehicle (A/V).
The A/V is relatively small with a length in the of ca. 2,3 meters, about 3,4 meters wingspan and a take-off weight of approx. 150 kg.

Air Data Terminal (ADT) (viewgraph 55)

The Air Data Terminal (ADT) of the BREVEL Data Link has been specifically designed taking into account the UAV constraints :

- **Aerodynamic:** the board antenna is installed in the tail fin of the UAV with minimum impact on the flight characteristics of the UAV.
- **Weight:** The Air Data Terminal has the lowest weight impact of all the electronic devices embedded in the UAV.
- **Thermal Conditions:** the electronics are divided in three units:
  - the Electronic Unit installed in the electronic bay of the UAV.
  - the Front-End (including power amplifier) installed in the rear of the UAV
  - the Board-Antenna on the tail-fin of the UAV.

  This permits to split the thermal dissipation and to dispatch it in the UAV and also to offer possibilities of growth potential. The Front-End and the Board-Antenna are the only frequency-sensitive components, and can be redesigned to suit the required transmitted power and/or frequency.
- **Accessibility:**
  - Antenna mounting occurs from the tail-fin side
  - Electronic Unit is installed on a trail in the electronic-compartment
  - Front-End has a small size and is easily accessible in the fuselage.

The Board-Antenna is pointed to the ground-station from a direction calculation based on A/V position, attitude and north-orientation. A special function compensates for eventual errors of the A/Vs north-reference.

The ADT features a MIL-BUS Interface to the A/Vs flight control system and RS 422 interfaces to the compression unit of the UAV camera to provide continuous on-line video.

The total ADT weight is in the order to 10 kg.

BREVEL Data Link Vehicle (viewgraph 56)

The BREVEL Data Link Vehicle (DLV) is a small 1-axel trailer, with a retractable fold-over mast, which carries the GDT and the power unit for GDT operation. The DLV can be located more than 1 km away from the manned Ground Control Station in order to protect personnel from anti-radiation weapons.

Ground Data Terminal (GDT) (viewgraph 57)

The Ground Data Terminal (GDT) of the BREVEL Data Link has been specifically designed taking into account the ground constraints :

- The GDT combines features of a precision tracking radar (without the radar transmitter) with the primary Data-

Link function. This way precise localization of the UAV is achieved.

- **Stabilization of the GDT:** due to the high level of accuracy for localization of UAV position through the Data-Link, a very performant stabilization of the ground antenna is mandatory.
- **Mechanical performances:** A sophisticated mechanical design has been chosen in order to handle the high performance antenna.
- **Protection:** the GDT is designed to conform with environmental constraints: NEMP, lightning, contamination with-out any damage.
- Communication with a remote control center through a fibre-optic link.

All GDT electronics and mechanics are located inside a spherical radome. Opening of the radome allows access to all components.

The GDT design allows tactical and logistical driving in most severe terrain without any damage to the high-precision mechanics and electronics. The overall weight of the GDT is about 160 kg.

Status of the BREVEL Data-Link (viewgraph 58)

DaimlerChrysler Aerospace and **MATRA Systemes & Information** have developed the BREVEL Data-Link between 1992 and 1998. A total of 17 Air Data Terminals and 5 Ground Data Terminals have been built for Industry Trials and Troop Trials.

The last deliveries have been made in April 1998 at the beginning of troop trials. Prior to that the BREVEL system has performed two flights in Finland in arctic winter climate. During these flights the data-link has performed without any failures. Long Range performance could be demonstrated during these flights.

More than 95 flights with data-link, amounting to over 90 flight-hours have occurred.

Germany has decided procurement of the BREVEL System and **STN ATLAS Elektronik** has received a contract for Serialization and Production of the System.

The serialization- and production-activities for the data-link by **DaimlerChrysler Aerospace** and **MATRA Systemes & Information** are planned to start in the third quarter of 1999.

Potential for Evolution (viewgraph 59)

Due to its modular design the BREVEL data link described above allows to adapt one or a few subunits to changing requirements without affecting the remaining part of the design. For example the following modifications could be envisaged.

- Antenna (different beamwidth, frequency range)
- Antenna stabilization (different accuracy)
- Front End (different transmitter-power, frequency band)
- Electronic Unit (different interface to A/V or ground station, increase of data-rate).

Also functions may be added (e.g. data compression) or deleted/simplified (e.g. A/V localization precision).
Such changes can be made without significant impact on the architecture of the design and with limited changes in software.
To summarize the design of the data link allows adaptation to a broad spectrum of requirements and has the potential to tailor its complexity to provide cost-effective solutions for requirements of extremely-high to medium sophistication.

SUMMARY (viewgraph 60)

UAV Data-Links have to satisfy requirements for

- maximum feasible range
- high mobility
- low mass and size
- high reliability and jamming resistance
- high data rates for such UAVs, which are equipped with imaging sensor.

If all of the above requirements apply no standard of-the-shelf solution exists and the data-link has to be designed to come to a cost-effective trade-off.

This may be done starting from an existing design. The BREVEL data link is an example, of a starting point, which satisfies all of the above requirements in a line-of-sight microwave data-link.

COTS solutions are available, which can satisfy a subset of the requirements

- The Mücke Link satisfies all of the requirements in an HF link with the exception of high data rates.
- The SATCOM link used in GLOBAL HAWK satisfies the requirements with the exception of low mass and size and with some restrictions on jamming resistance.

These examples show that all variants

- HF
- Microwave
- SATCOM

have their place in the UAV world.

DaimlerChrysler Aerospace is the Competence Center in Germany for UAV Data Links and is one of the leading developers and suppliers for Microwave and HF Data-Links.

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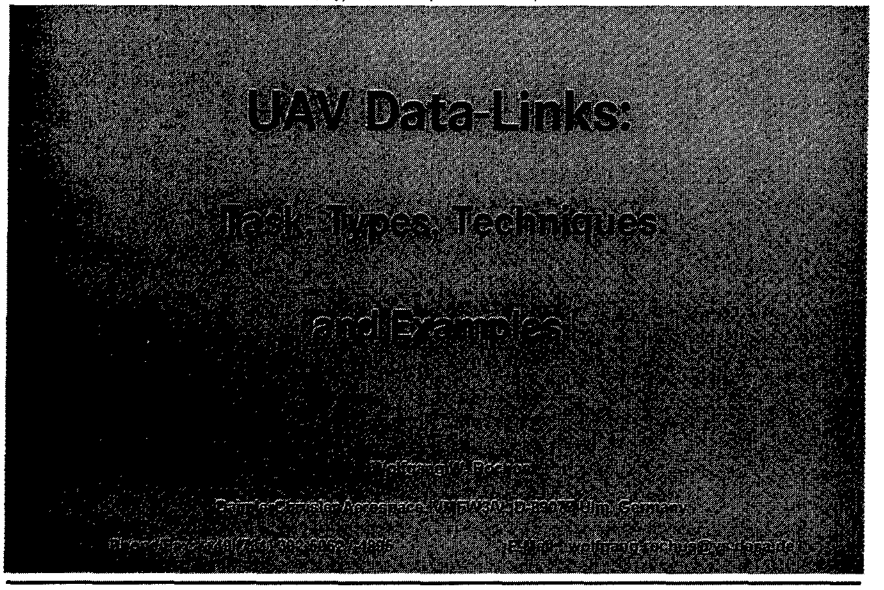
UAV Data-Links: Tasks, Types, Techniques and Examples



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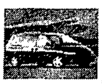
DaimlerChrysler AG

1998 : Revenues DM 257.8 bn / € 131.8 bn
Workforce 442,000

Automotive			Non-Automotive			
Passenger Cars	Passenger & Commerc. Cars	Commercial Vehicles	Aerospace	Chrysler Financial Services	Services	Other Businesses
						
▪ Mercedes-Benz ▪ Smart	▪ Chrysler ▪ Plymouth ▪ Jeep ▪ Dodge	▪ Mercedes-Benz ▪ Freightliner ▪ Sterling ▪ Setra	▪ Commercial Aircraft ▪ Helicopters* ▪ Military Aircraft ▪ Defense and Civil Systems ▪ Aero Engines ▪ Space Infrastr. ▪ Satellites *40% stake	▪ Leasing ▪ Commercial Financing ▪ Conventional Financing	▪ Financial Services ▪ Telecom-munication & Media Services ▪ IT Services	▪ Rail Systems ▪ Automotive Electronics ▪ MTU/ Diesel Engines
Revenues DM 63.8 bn € 32.6 bn Workforce 95,200	Revenues DM 110.1 bn € 56.3 bn Workforce 123,200	Revenues DM 45.4 bn € 23.2 bn Workforce 89,700	Revenues DM 17.2 bn € 8.8 bn Workforce 45,900	Revenues DM 5.7 bn € 2.9 bn Workforce 3,500	Revenues DM 18.8 bn € 9.6 bn Workforce 20,200	Revenues DM 6.6 bn € 3.4 bn Workforce 32,600

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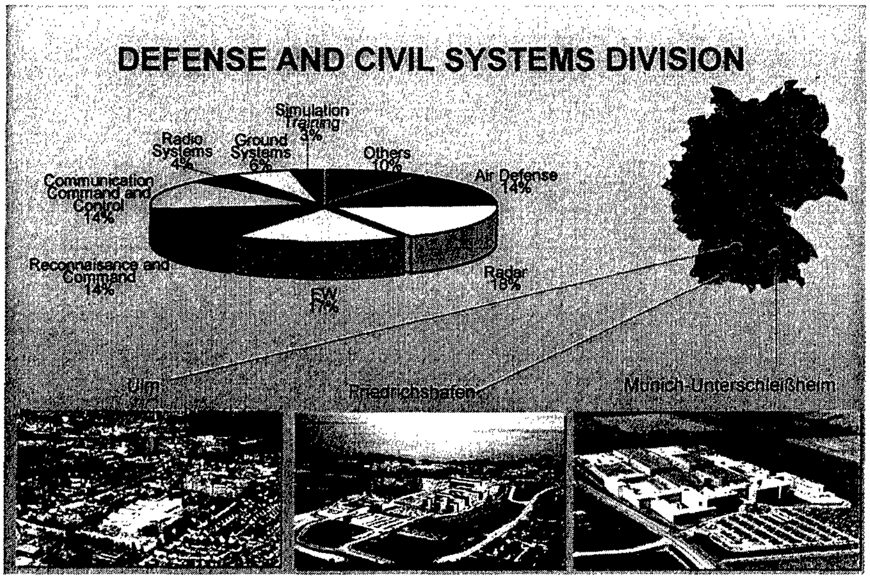

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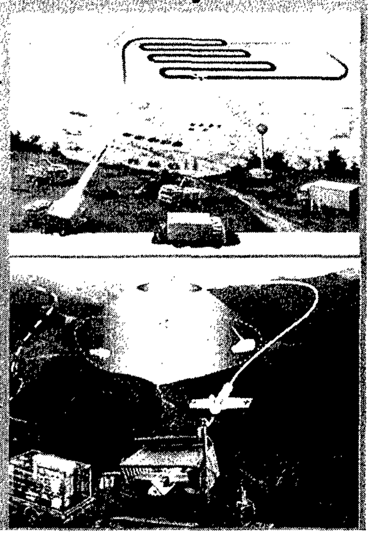
DASA ULM - Data-Links for UAV and Missile-Systems

Current Data-Link Projects:

- **KZO BREVEL Data-Link** (production-ready)
- **Naval Drone SEAMOS DL** (Definition Phase)
- **CL289 Data-Link Upgrade** (Feasibility Study)
- **Data-Link for HALE UAV** (Feasibility Study)
- **Data-Link for ESM-UAV** (Feasibility Study)
- **Data-Link for Naval Stand-off weapon KEPD-150 SLM** (Feasibility Study)
- **ROLAND Surface to Air Missile Data-Link** (After Sales Support)
- **MEADS Surface to Air Missile Data-Link** (Feasibility Study)
- **MJ2000 Sonar-Data Transmission** (Definition Phase)
- **HF-Data-Link for Mücke Jamming Drone** (Development)
- **HF-Data-Link for TAIFUN Attack Drone** (Definition Phase)



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UAV DATA - LINK

TASKS AND REQUIREMENTS

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UAV Data-Links: Tasks, Types, Techniques and Examples

TYPICAL UAV MISSIONS

Reconnaissance, Surveillance, Damage Assessment

• Suppression of Enemy Air Defense (SEAD)

• Target Search and Attack

• Target Localisation for Artillery Engagement

• COMINT and ELINT

• Jamming

MOST OF THESE MISSIONS REQUIRE A DATA-LINK

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MISSION NEEDS FOR DATA-LINKS IN UAVS

- [illegible] OF UAV AND/OR PAYLOAD
  ([illegible] UPLINK (TELECOMMAND))
- STATUS INFORMATION FROM UAV AND/OR PAYLOAD
  ([illegible] DOWNLINK (TELEMETRY))
- [illegible]
- [illegible] ANGLE TO UAV

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General Requirements for UAV Data Links

General

- Range: 20 to 300 km, line-of-sight or non line-of-sight
- [illegible]
  - [illegible]: 75 to 1200 bits/s
  - [illegible]
- [illegible]

[illegible]

General Station

- [illegible]

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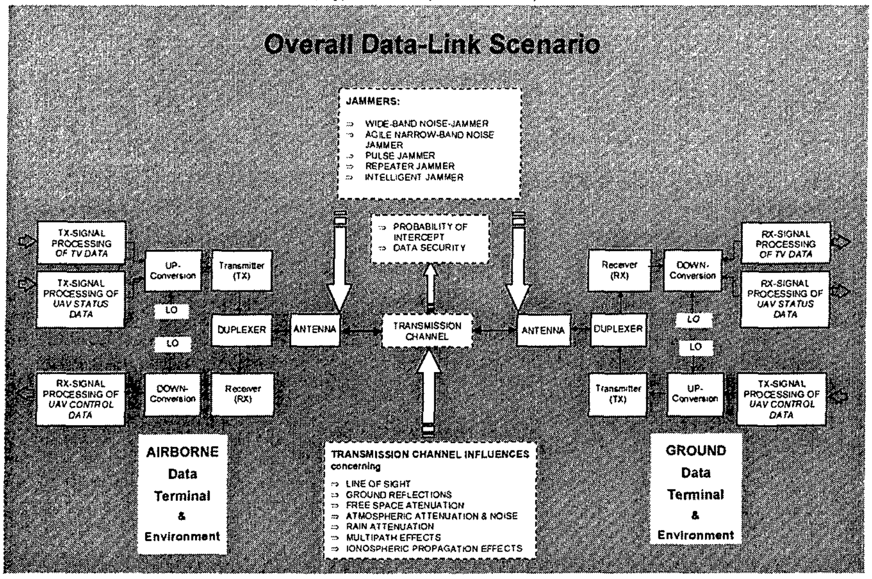

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UAV DATA - LINK

TYPES AND GENERAL CHARACTERISTICS

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UAV Data-Links: Tasks, Types, Techniques and Examples

ANALOG versus DIGITAL

- Analog Links transmit the information by means of amplitude- , frequency- or phase-modulation
  (e.g. AM/FM Broadcast, Television)

  They are still in use in many UAV systems.
  These links are generally not jam-resistant and robust.

- Digital Links convert the analog signal into a digital data-stream, which is transmitted by means of Phase-Shift- or Frequency-Shift-Modulation.

  This allows to manipulate the signal in such a way that a great degree of jam-resistance and robustness can be achieved

  They are the Future

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Data-Rate and Bandwidth

Robust Standard Modulation Techniques (e.g. BPSK) usable for UAV Data-Links require:

> Data-Rate r (Bit/s) ≈ net Band-Width B (Hz)

For technical reasons feasible band-width is related to transmitted frequency:

> max. usable Bandwidth B(Hz) ≈ 3% of Transmit Frequency (Hz)

Jam-Resistance can be achieved by multiplying the net band-width:

> Approximation for jam-resistant UAV-Data-Links:
>
> Bandwidth B (Hz) ≈ 2...1000 * Data-Rate r (Bit/s)

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Frequency Bands for UAV Data-Links

Frequency	Band	Characteristics
100GHz – 1GHz	Micro-Wave: (SHF)	- Generally Line-of-Sight Communication - high gain with small antennas - narrow beam antennas possible - high data-rates possible - *limited transmitter efficiency*
1GHz – 100MHz	VHF / UHF:	- Propagition by LOS or Reflection and Diffraction - relatively large antennas - Data-Rates limited to <2MBit/s
10MHz – 1MHz	Short-Wave: (HF)	- no Line of Sight required - Ground- or Sky-Wave propagation - dependent on solar activity, time of day, location - only low data-rates (<10kBit/s) feasible
1MHz – 100kHz	LW, MW	

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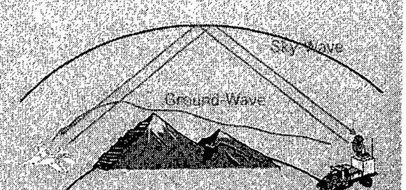
UAV Data-Links at HF-Frequencies (Shortwave)

Propagation not dependent on Line-of-Sight:

1. Ground-Wave (Deflection, Reflection, Diffraction)
2. Sky-Wave (Ionospheric Reflection)



Typical Characteristics:

1. Link Quality very dependent on Time, Location and Frequency
2. Low Data-Rates (<10kBit/s) due to low frequency and propagation effects
3. Frequencies above ca. 12 MHz cannot be used reliably in a UAV System
4. Range up to ca. 500 km with > 90 % availability, independent at UAV altitude

HF UAV Data-Links allow long-range communication without line of sight.
Due to limited data-rates at HF they are limited to Telecommand or Telemetry Data and Transmission of still images.

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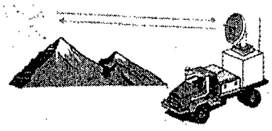
UAV Data-Links at Microwave



Characteristics of Microwave Data-Links:

- Line of Sight Propagation (LOS)
- Range up to a few 100 km (dependent on UAV altitude and terrain)
- High Transmit Frequency allows extremely high Bandwidth (several 100 MHz)
- High Bandwidth allows High Data-Rate and optimum Jamming Resistance
- High Transmit Frequency facilitates Narrow-Beam Antennas (Jammer Suppression, LPI)
- Long Range independent of UAV altitude and terrain requires an Airborne Relay

For small tactical reconnaissance UAVs a LOS-Microwave-Data links provide an optimum solution as they can combine high data-rates with optimum jamming resistance at reasonable size and weight.

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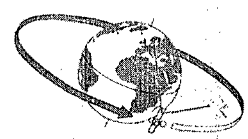
UAV Satellite Links



General Characteristics:

- World-Wide Coverage possible. Only depends on Number and Orbit of the Satellites used
- Extremely high Data-Rates (>100MBit/s) possible due to high transmit frequency and line-of-sight condition

Problems / Restrictions:

- UAV Antenna-System for wide-band transmission of sensor data is heavy and big
- Uplink UAV-> Satellite can be jammed with relative ease
- Military Communication Satellites are currently not in the inventory of european countries.

Wide-Band satellite-based Data-Links are primarily used for HALE-UAVs (HALE: High Altitude, Long Endurance) which require world-wide coverage and can tolerate high volume and mass. Wideband-Satellite-based links are currently not yet an alternative for smaller (tactical) UAVs !

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UAV DATA - LINK

DESIGN ASPECTS & TECHNIQUES

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UAV Data-Links: Tasks, Types, Techniques and Examples

MAIN CONSIDERATIONS FOR DATA-LINK DESIGN

- AIR VEHICLE CONSTRAINTS
  - antenna type and size, transmitter power
  - Size, Weight and Power Consumption
- LINK BUDGET AND QUALITY
  - gain and losses balance for Signal to Noise Ratio
- LINK PROTECTION AND QUALITY
  - side-lobe suppression
  - robustness of modulation
  - anti-Jamming techniques
- FLEXIBILITY, COMPLEXITY AND COST

➔ TRADE-OFFS ARE REQUIRED

Definition of the System Quality Figure of a Communications Link

System Quality =	Radiated Power from Tx in the direction toward Rx	–	Minimal Detectable Signal Power (Rx Sensitivity) of Rx in the direction toward Tx	=	Maximum Allowable Path Loss

Radiated Power:

- Nominal Transmitter Power
- Modulation Loss (Crest Factor)
- Antenna Matching / Matching loss
- Antenna Gain (Directional Gain x Efficiency) in the direction towards Rx (Elevation, Azimuth)

Minimal Detectable Signal:

- Receiver Noise Figure
- Antenna Matching / Matching Loss
- Antenna Gain (Directional Gain x Efficiency) in the direction towards Tx (Elevation, Azimuth)
- Bandwidth (Data Rate)
- Minimal Signal / Noise (S/N) Ratio (dependent on Modulation Type)

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UAV Data-Links: Tasks, Types, Techniques and Examples

Link-Budget: Data-Link Signal Power

Power density at distance d:

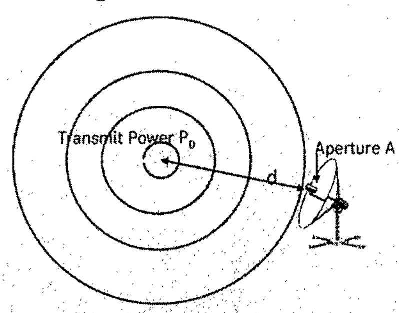
$p = P_0 / (4\pi d^2)$

Signal Power at Antenna:

$P = p A = P_0 A / (4\pi d^2)$

Antenna Gain G in dB:

$G = 10 \log (4\pi A / \lambda^2)$



Received Signal Power at RX input in dBm (dB above 1 mW) is thus calculated as

$$S/dBm = P_0/dBm + G - 10 \log (4\pi d/\lambda)^2$$

- Signal Power at RX (dBm)
- Transmit Power (dBm)
- Antenna Gains (Airborne + Ground)
- Free Space Attenuation as a Function of Range and Wavelength

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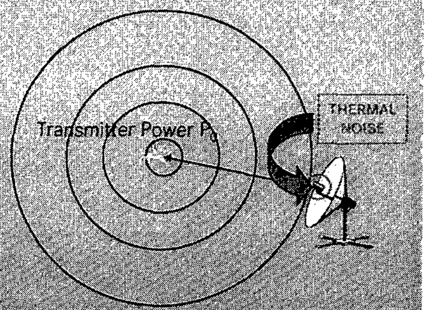
Link-Budget: Noise Power

Thermal Noise is the result of molecular movement in the components of the receiver. Thermal Noise Power is given as

$N = k\,T_0\,B$

k = Boltzmann-Constant $1{,}38 \cdot 10^{-23}$ Ws/K
T = Temperature (generally 300K)
B = Receiver Bandwidth



Considering the Relation Bandwidth $B \approx$ Data-Rate r and the constants k and T_0 Noise Power at the receiver input can be derived from the formula

$$N/\text{dBm} = -174\text{dBm} + 10\log(r)$$

Noise Power at Rx (dBm) — Constant: $10\log(kT_0)$ — Data-Rate dependent

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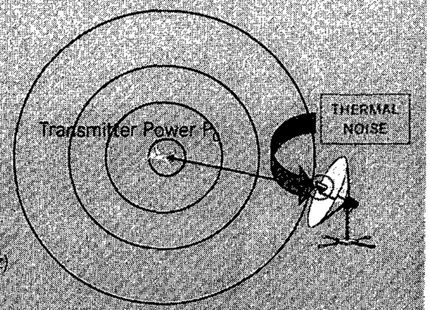
Link-Budget: Signal-to-Noise-Ratio (SNR)

Signal-to-Noise-Ratio allows an initial rough judgement of data-link performance.
It includes the major influences.
Further influences are introduced by

- Cable and Radome losses, etc.
- Losses from multi-path effects
- Synchronization Losses
- Weather attenuation (e.g. 0,1dB/km at 10GHz)
- Jamming



The Signal-to-Noise-Ratio at the Receiver can be calculated as:
(atmospheric noise and jamming not taken into account)

$$\text{SNR} = 10\log\frac{P_0 \cdot g \cdot \lambda^2}{k \cdot T_0 \cdot r \cdot (4 \cdot \pi \cdot d)^2} = P_0/\text{dBm} + G - 10\log(4\pi d/\lambda)^2 - 10\log(kT_0 r) \overset{!}{\geq} 10\text{dB}$$

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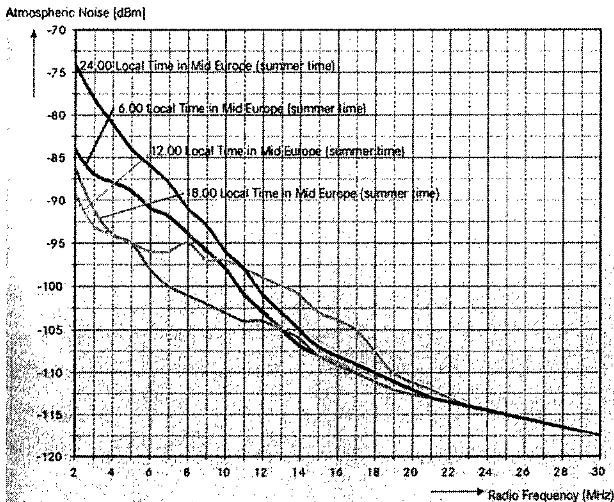

Atmospheric Noise as a function of Radio Frequency at different local times (Winter, Sun Spot Number = 75, Mid Europe)

Frequencies above ca. 12 MHz are generally not reliable for use in a UAV System

Minimum Sensitivity is largely determined by atmospheric noise

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UAV Data-Links: Tasks, Types, Techniques and Examples

Typical Path-Losses and Antenna Parameters for UAV Data Links

Frequency (GHz)	λ (cm)	Free-Space + Atmospheric Attenuation for 180 km	Free-Space + Atmospheric + Rain Attenation for 180 km	Total Gain ADT+GDT Antenna (dBi)	Az-Beam (GDT)	AZ-Beam (ADT)
0,4	75	130 dB	130 dB	≈ 20	≈ 25°	360°
2	15	145 dB	145 dB	≈ 25	≈10°	360°
5	6	153 dB	153 dB	≈ 40	≈ 4°	≈ 35°
10	3	159 dB	162 dB	≈ 55	≈ 2°	≈ 12°
15	2	164 dB	171 dB	≈ 65	≈ 1°	≈7°

Rain is assumed with a density of 4mm/h over 25% of the path

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Link-Budget: Examples

Examples for a UAV-Data-Link in Ku-Band (15 GHz) for TV-transmission (r=5 Mbit/s):

Influence	Example1 (Omni-directional Antenna)	Example 2 (Directional Antenna)
SNR required	10dB	10dB
Noise Power at r=5MBit/s	-107dBm	-107dBm
Free Space Attenuation for 100km	156dB loss	156dB loss
Rain Attenuation (0,15dB/km)	15dB loss	15dB loss
Receiver Noise Figure	3dB loss	3dB loss
Antenna Gains (Airborne + Ground)	0dB gain	64dB gain
System Losses	4dB loss	4dB loss
Fading Margin	10dB loss	10dB loss
Required TX Power in UAV	91 dBm = 1200 kW Not feasible!	27 dBm = 0,5W

This Link-Budget for a typical UAV Data-Link makes it obvious that directional high-gain Antennas are mandatory.

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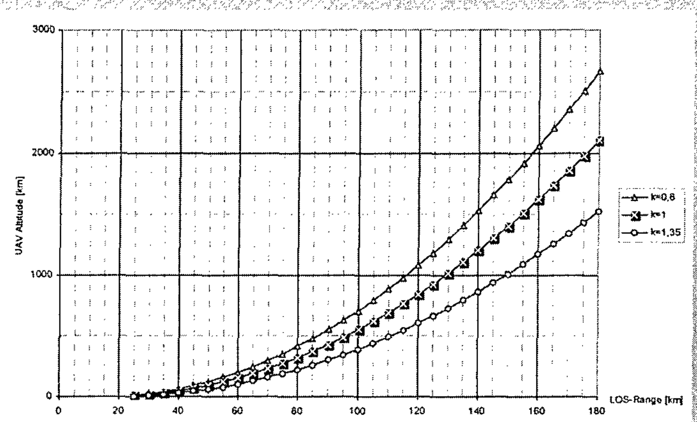
Line of Sight Range of Microwave Link vs. UAV Altitude



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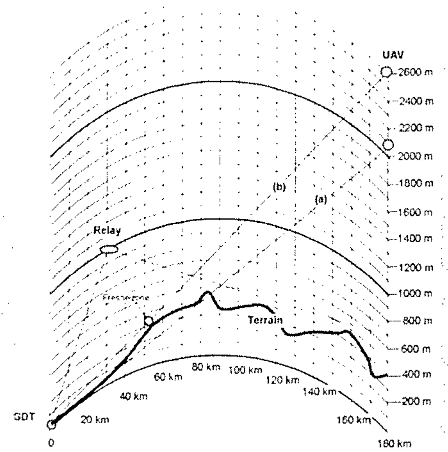
Terrain Masking Effects on Line of Sight Range



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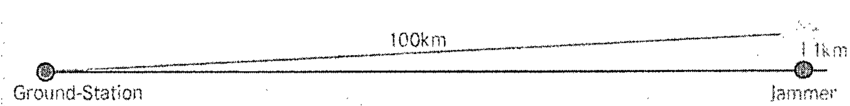
Jamming - Resistance



For equal transmitter power of ground-station and Jammer the UAV receiver sees:

Jamming Power $J = 100^2 \bullet$ Power of Data-Link Signal --> Factor of 10000 equals 40dB !

Suppression of Jammers can be achieved by:

- Narrow-Beam Antennas
- Direct-Sequence Spread-Spectrum
- Frequency-Hopping Spread-Spectrum
- Channel Coding

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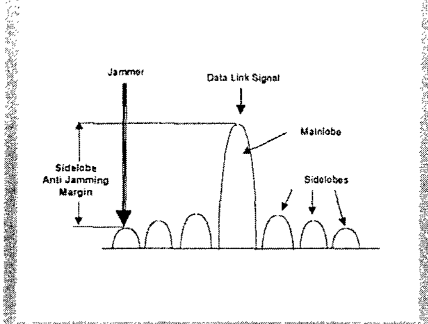
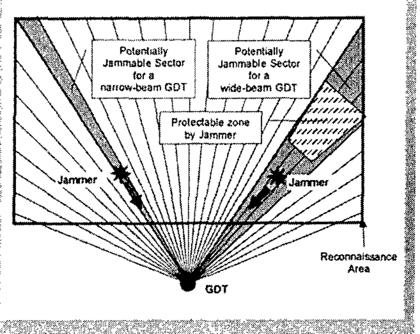
Anti-Jamming Effect of Highly Directional Antennas





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Suppression of Jammers by Narrow-Beam Antennas

- Jammers are largely limited to the main-lobe
- Jammer Suppression $\geq$ Side-Lobe suppression (e.g. > 20dB)
- Width of main-lobe is inversely proportional to antenna size
- Width of main-lobe is inversely proportional to frequency
- Jammable area decreases with beam-width

Directional Antennas should be used in the UAV and on ground!
For a given antenna-size jammer suppression increases with frequency!

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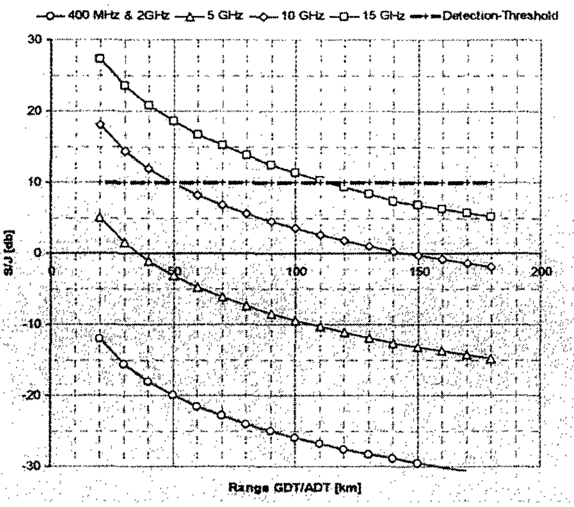
Down Link Range under Severe Jamming Conditions



Power: 1 W

Antenna Gain (ADT)
Size - limited by constraints of tactical UAVs

typically between 1 dBi at 0,4 GHz and 23 dBi at 15 GHz

Antenna Gain and Sidelobes (GDT)
Size - limited by cross-county capable Data-Link Vehicle

typically between -15 dB side-lobes and 18 dBi gain at 0,4 GHz and -28 dB side-lobes and 40 dBi gain at 15 GHz

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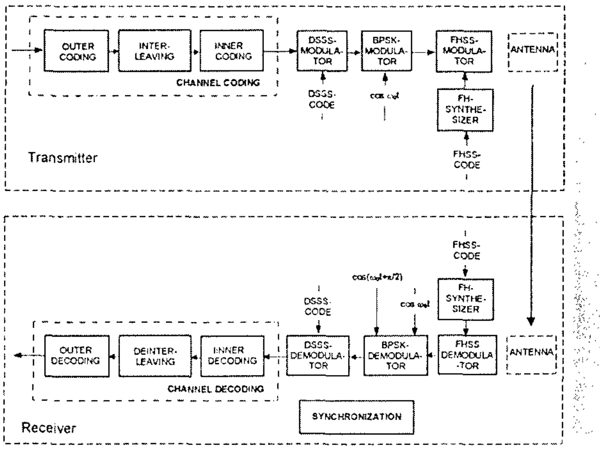
Typical Digital Data-Link Processing



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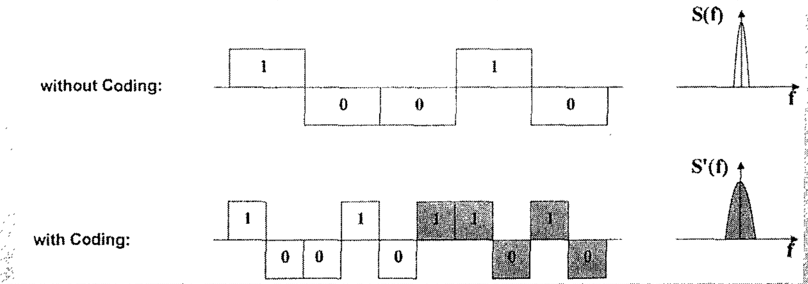
Channel Coding for Improvement of Bit Error Rate (BER)



TX Side:	Introduce Redundancy (additional Bits according to Coding Algorithm)
RX Side:	Use Redundancy to Detect and Correct Bit-Errors
Result:	In spite of increased bandwidth for the same TX-Power (➡ lower S/N) the Bit-Error-Rate can be reduced
Examples:	Block-Codes: BCH-Codes, Reed-Solomon-Codes, Hamming-Codes, CRC Convolutional Codes: various constraint lengths and generator-polynomes

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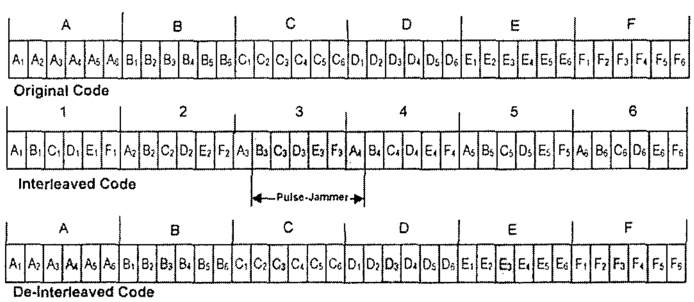
Anti-Jamming Effect of Interleaving



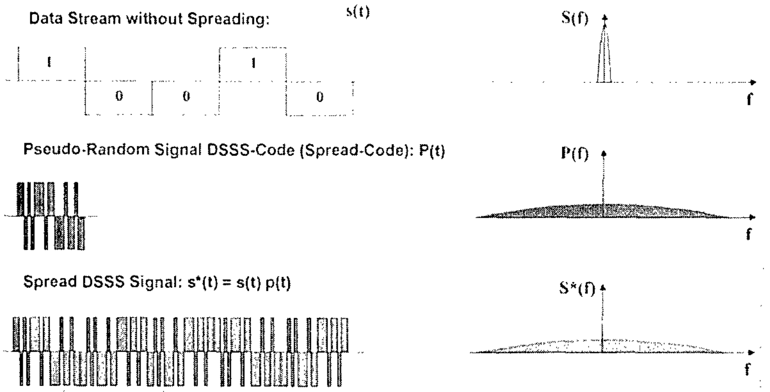
Effect of Pulse Jammer can be transformed to limited effects, which can be corrected by Error-Correction Coding

Generation of Direct-Sequence-Spread-Spectrum (DSSS)

Data Stream without Spreading:

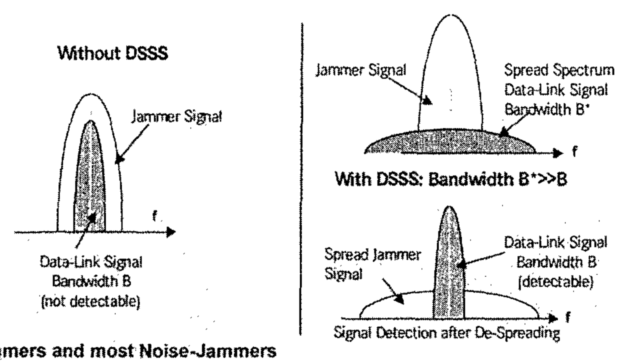
Pseudo-Random Signal DSSS-Code (Spread-Code): P(t)

Spread DSSS Signal: s*(t) = s(t) p(t)



The transmitted DSSS Signal is generated by multiplication of the digital data-stream and a spread. This results in a wide-band signal with low spectral density, which facilitates Jamming-Resistance and Low-Probability of Intercept.

ANTI - JAMMING EFFECT of Direct Sequence Spread-Spectrum



Spot-Jammers and most Noise-Jammers can be suppressed by DSSS

Processing Gain=Spreading Factor = B*/B

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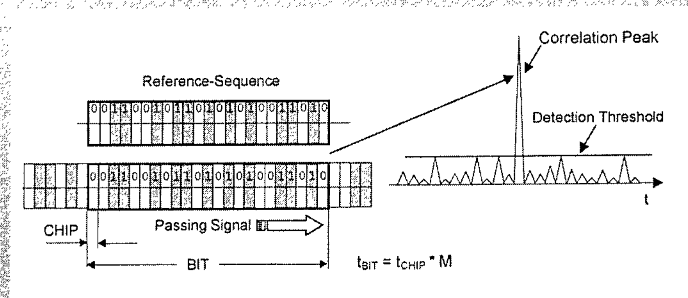
DE-SPREADING OF DSSS SIGNAL BY CORRELATOR



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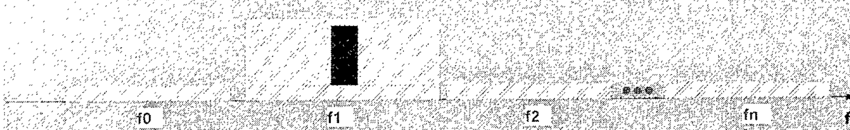
Frequency Hopping Spread Spectrum



Pseudo-Random Change of Center-Frequency Between N Channels

- forces jammer to spread energy over n channels
  >> jammer efficiency reduced by 1/n
- effect of jammer, which stays in only 1 channel
  can mostly be compensated by channel-coding
- Fading- and Multipath-Effects are minimized by FHSS

Design Summary for Wide-Band Data-Links

Design Feature	Reason / Potentaial
Use of Ku-Band (15 GHz)	• NATO-Recommendation for future UAV-Data-Links • facilitates high bandwidth • narrow antenna-beam Jam-Resistance
Directional Antenna (Ground and Airborne)	• Best Link Budget (Range) • low probability of intercept (LPI), high jamming resistance • allows UAV position measurement and tracking • Minimization of multi-path effects (stability)
Direct-Sequence Spread-Spectrum	• low probability of intercept (LPI), high jamming resistance • precision measurement of UAV range
Frequency-Hopping Spread-Spectrum	• further improvement of LPI and jamming resistance • Minimization of multi-path effects by inherent Frequency-Diversity
Optimized Channel Coding	• Improvement of Bit Error Rate at given S/N • Correction of Clustered Errors from Pulse Jammers

UAV DATA - LINK

EXAMPLES

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UAV Data-Links: Tasks, Types, Techniques and Examples

UAV Satellite Links - Example: Global HAWK

Characteristics of HALE-UAVs:

- Range ca. 25000km
- max. altitude ca. 20000m
- Mission-Time up to ca. 40h
- Sensors: SAR, EO, IR, MTI, ...

Characteristics of the SatCom-Link:

- Uplink UAV -> Satellite in Ku-Band (15GHz)
- Data-Rate 1,5MBit/s (one channel) up to 47MBit/s (multiple channels)
- Commanded Parabolic Dish (∅1,25m)

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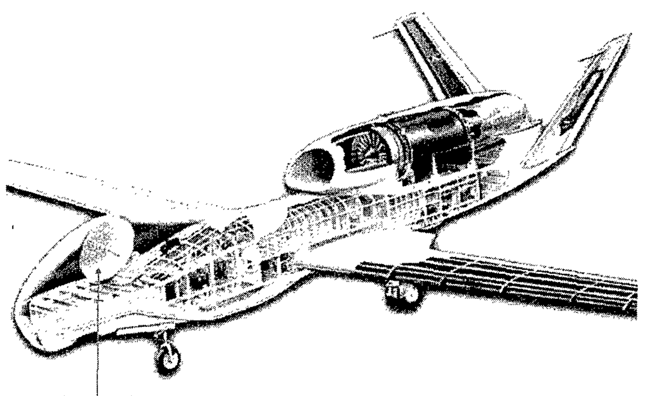
UAV Satellite Links - Example: Global HAWK



Ku-Band SatCom-Antenna with 1,25m diameter
Stabilization and Pointing of the Antenna requires ~1m^3 Volume

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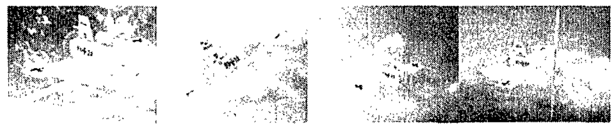
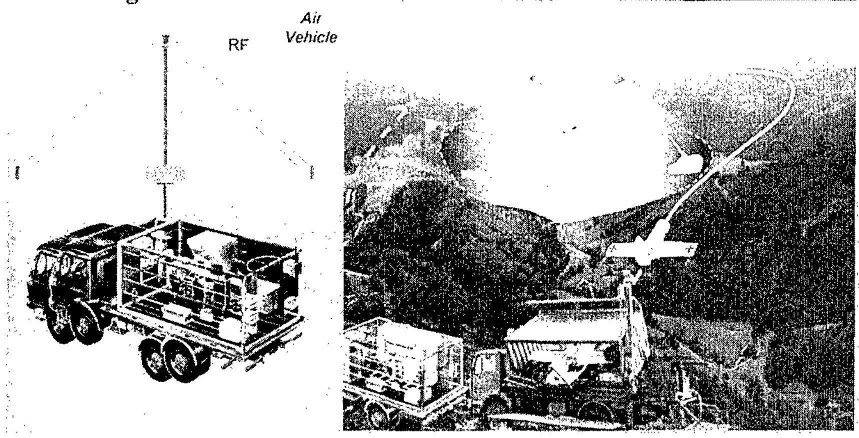
UAV Data-Links Tasks, Types, Techniques and Examples

Example: HF Data Link for MÜCKE Jamming Drone





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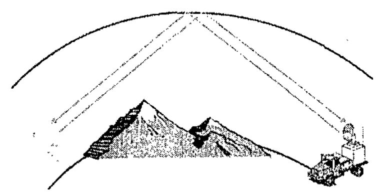
HF UAV Data-Links
Example: Jamming Drone MÜCKE



HF Data-Link Characteristics

- Bidirectional Link (TC-Uplink and TM-Downlink)
- Multiple Transmission, FEC-Coding, Frequency-Diversity and cyclic Frequency-Hopping to maximize Link-Availability
- Data-Rate ≈ 1kBit/s, Range ≈ 400km, Availability 70% bis 90%

Data-Link Tasks

- Uplink TC: Control of Jammer, Request for Status and Position, Change of Mission Planning
- Downlink TM: Status and Position Reporting

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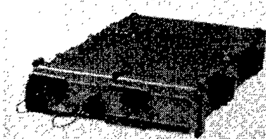
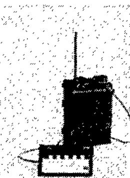
UAV Data-Links: Tasks, Types, Techniques and Examples

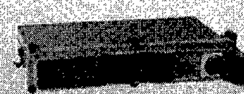
HF Radio Mobile HRM 7000 (portable)

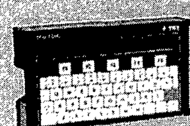


HF-Transceiver HRU 7000
- HF Output Power 30 Watt
- Link Control Processor
- HF Modem



Antenna Tuning Unit ATU 7000
- Whip Antennas 3,3m to 7m
- Long Wire Antennas 7m to 16m
- Dipole Antenna DPA 7000





Terminal TCU 7000
- Display 2 lines, 40 characters
- Soft-Key Man Machine Interface
- 2x Memories for Report and Command Messages
- Embedded Crypto Unit

Power Supply
- Accumulator Power Unit APU 7000 (NiCad, 5Ah)
- Battery Power Unit BPU 7000 (Lithium, 20Ah)

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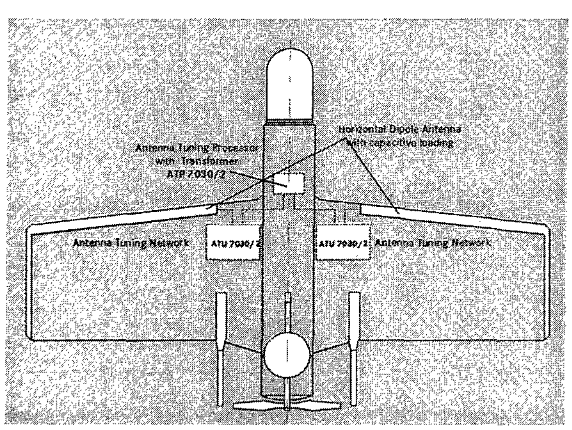
MÜCKE JAMMING UAV



MÜCKE
GROUND CONTROL STATION
WITH
GROUND DATA-LINK TERMINAL

Horizontal HF Dipole Antennas integrated in Drone (electrical length extended via capacitive loading)

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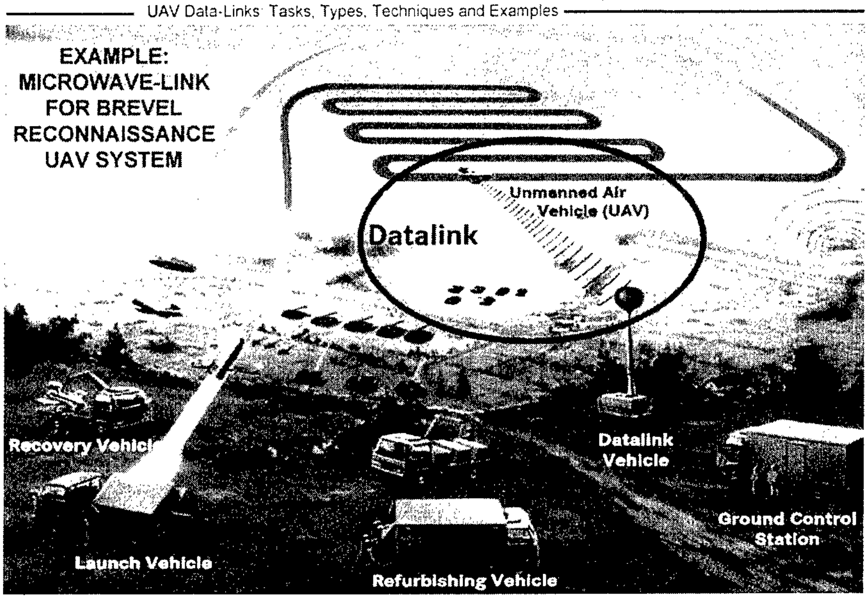

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BREVEL Operational Tasks:

- **Reconnaissance over the Battlefield**
- **Target Detection**
- **Target Localization for Engagement by MLRS, SMArt 155, etc. to maximum weapon-range**
- **Mission Time : several Hours**

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Design Drivers for BREVEL Data-Link:

Provide Television and Status Downlink & Control Uplink with

- Extremely High Jamming Resistance
- Low Detection Probability of Data-Link Signals
- Error Correction Capabilities
- Very high Accuracy for Measuring the Drone's Location
- High Electromagnetic Compatibility Requirements (NEMP)
- Flexibility in Changing of Codes for Each Mission

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BREVEL DATA-LINK DESIGN CHOICES

- **A Digital Data-Link allows**
  - forward error correction
  - most performant spread spectrum techniques
- **A Full Duplex Data-Link**
  - allows very accurate synchronisation of transmitter and receiver
  - improves spread spectrum performance
  - allows precise measurement of propagation delay
- **Highly directive Antennas**
  - allow tracking and angle-measurement
  - improve link budget and jam-resistance

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Localization Function

Achieved through

- precise angle-measurement in GDT by monopulse principle
  (Sum- and delta-channel with sophisticated signal processing)
- calculation of ADT range from propagation delay
  (accurate measurement by spread spectrum synchronisation algorithm)

Gives exact coordinates for engagement of the targets in the footprint of the UAV's imaging sensor

Allows extremely narrow antenna beam in GDT for

- **improvement of link budget**
- **jamming protection**
- **ADT tracking by GDT**

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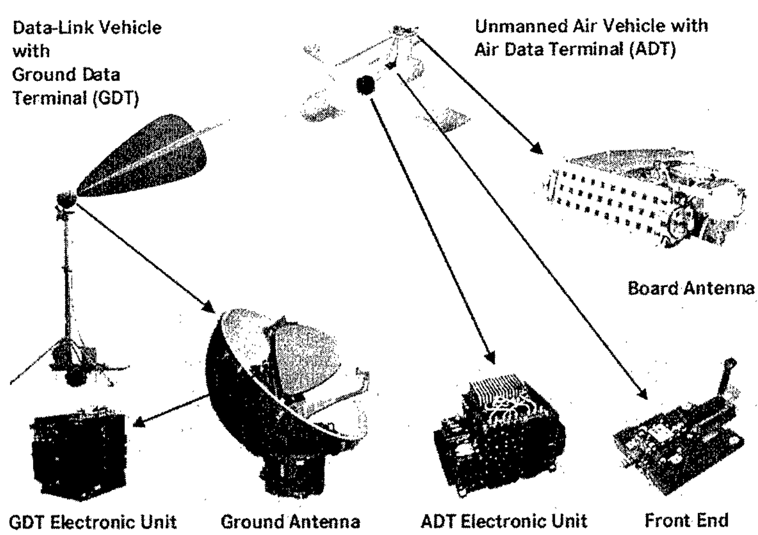

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UAV Data-Links: Tasks, Types, Techniques and Examples

Key Design Features:

- Frequency Band: Ku-Band
- Range: > 150 km
- Data Rates Uplink: 10 kb/s Command Channel
  Downlink: 10 kb/s Status Channel
  10 Mb/s Payload Data
- Full Duplex
- Combined Frequency Hopping- and Direct Sequence Spread Spectrum
- 2-Level Channel Coding optimized for anti-jamming
- A/V Localisation and Tracking (Range and Azimuth)
- Highly directive Antennas with automatic tracking
- Solid State Transmitter with adaptive Power Management capability
- Field Servicable (LRU Concept)
- Highly Modular
- Very low Bit- and Frame Error Rates

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BREVEL Air-Vehicle

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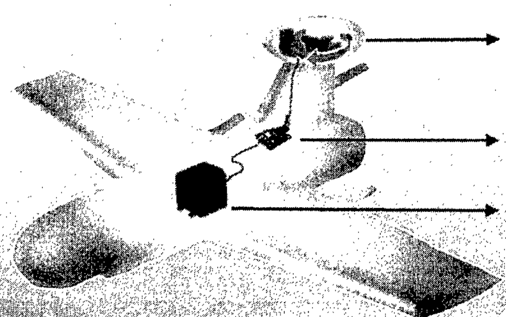
Air Data Terminal (ADT)



Modular Construction
allows adaption to
- Thermal and Space Constraints
- Future Changes in Power and Frequency
gives optimum maintainability

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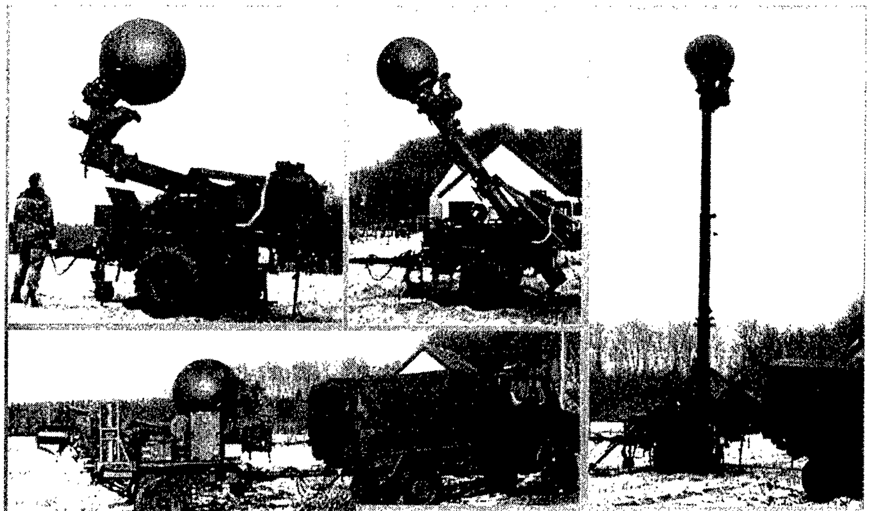

BREVEL Data-Link Vehicle

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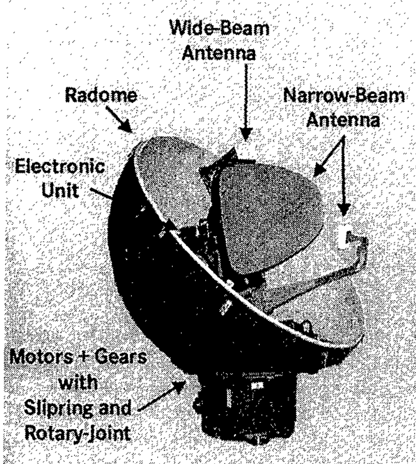
Ground Data Terminal (GDT)



combines
RADAR TECHNOLOGIES
for precision tracking
of air-vehicle

and
SIGNAL PROCESSING TECHNOLOGIES
for error-free jam-resistant
communication

with
FIBER-OPTIC LINK TO GROUND-CONTROL STATION
for EMC and NEMP Protection

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STATUS OF BREVEL DATA-LINK

- 17 Airborne Data Terminals (of 22) and
- 5 Ground Data Terminals (of 7)

built for Industry-Trials and Troop Trials until April 1998

- Troop Trials under way since April 1998
- More than 95 data-link flights (> 90 hours)
- 2 flights in artic climate
- Serialization/Production Start planned for 3rd quarter of 1999

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GROWTH POTENTIAL

Modular Design and flexible Architecture allow

- **Range Increase by Simple Exchange of Power Stage**
- **Advanced Adaptive Power Management Algorithms**
- **Change of Interfaces**
- **Addition of Functions (e.g. data compression)**
- **Data Rates up to 50 Mb/s without change of concept**
- **Change of Frequency Band possible with partial exchange of subunits only**

Summary

- UAV Data-Links are subject to complex requirements
  - high mobility
  - high data rates
  - high jamming resistance
  - low mass and size
- Military UAV Data-Links are usually adapted or designed to offer an optimum trade-off between these requirements for the specific application
- Major Variants
  - HF Link
  - Satellite Link
  - Microwave Link
- DaimlerChrysler Aerospace, Ulm, is the German Competence-Centre and leading System Supplier for UAV Data-Links