INSTANTANEOUS IMPACT POINT PREDICTION FOR SOUNDING ROCKETS – PERSPECTIVES AND LIMITATIONS

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ABSTRACT

Accurate knowledge of the instantaneous impact point (IIP) is a key requirement for range safety operations during a sounding rocket launch. This paper discusses various tracking systems and trajectory models employed for IIP prediction by SSC and DLR and presents a novel GPS based onboard IIP sensor. Flight data from the Maxus-4 and -5 missions conducted at ESRANGE, Kiruna, are discussed to demonstrate the benefit of GPS based range safety over radar systems. The VS-30/Cuma mission, in contrast, is used to point out inherent limitations in the forecast of aerodynamic effects encountered in extreme, non-nominal flight situations.

1. INTRODUCTION

The instantaneous impact point (IIP) describes the touch-down point of a sounding rocket under the assumption of an immediate end of the propelled flight. It is representative of a situation in which the rocket motor is instantaneously switched off by the mission control center following e.g. a guidance error during the boost phase. As part of the range safety operations during a sounding rocket launch, a real-time prediction of the IIP is performed to monitor the expected touch down point in case of a boost termination. The computation and display of the IIP allows the range safety officer to discern whether the rocket would eventually land outside the permissible range area and thus necessitate an abort of the boosted flight or even a destruction of the malfunctioning vehicle.

In the subsequent sections, we discuss the fundamental principles of IIP based flight terminations systems and provide various results from actual missions. Special focus is given to the use of GPS tracking, which has recently been incorporated into the operations of ESA's Maxus and Texus program. Aside from providing new standard for accurate and low cost tracking systems, GPS sensors provide the added benefit of onboard availability of the navigation information. This will eventually enable the design and implementation of fully autonomous flight termination systems.

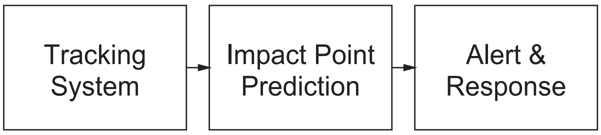

Fig. 1 Fundamental building blocks of an IIP prediction based flight termination system

2. METHODOLOGY

An IIP based flight termination system involves three core components, which are illustrated in Fig. 1:

1. In a first step, the current state vector of the vehicle with respect to an adopted reference frame must be determined.
2. This state vector is then propagated to forecast the expected impact point of the vehicle.
3. Finally, the criticality of the predicted IIP must be assessed and the respective action (e.g. destruction command) be taken.

Depending on the systems concept, each of these steps can be performed either on ground or onboard the vehicle.

2.1 Tracking Systems

At Esrange, the prime site for launches within the European microgravity program, C-band radar systems have traditionally been used to track the flight paths of sounding rockets. The AN/MPS-36 and RIR-774C radars (Fig. 2) provide high-rate angular and distance measurements with typical noise values of 1 mrad (200") and 1 m, respectively [1]. While the three-dimensional position vector of the tracked vehicle is directly provided by the available measurements, the corresponding velocity vector must be obtained by suitable filtering and differentiation.

Aside from radar tracking, a one-way ranging system built around the S-band telemetry system has successfully been operated at Esrange [2]. It employs a highly stable, oven controlled oscillator (OCXO) installed onboard the rocket. The output of this oscillator is modulated on the S-band carrier and the range change since lift-off can thus be obtained on ground from measurements of the integrated carrier beat phase. Together with the antenna pointing angles, a three-dimensional position measurement is provided by the system, which may again be differenced to obtain the full state vector information. While the achievable ranging accuracy of 100 m is inferior to radar, it is still sufficient for range-safety purposes and the one-way ranging system has long been essential to ensure the redundancy in case of radar failures.

Fig. 2 MPS-36 radar at Esrange, Kiruna

Only a single radar and the supplementary one-way ranging system are generally available for Esrange mission support. Both are installed in the immediate vicinity of the launch site and the resulting state vector estimates are particularly sensitive to systematic errors in the azimuth and elevation measurements. Great effort is therefore required to always ensure a proper calibration of the angle decoders. To overcome this deficiency, a tri-lateration system employing three radars at a mutual separation of about 100 km would be required. However, this is presently infeasible concerning both site access and cost aspects.

As a supplement or replacement for traditional radars systems, GPS tracking of sounding rockets has therefore gained an ever growing interest over recent years. Following a series of initial qualification flights, GPS is today considered as a promising and feasible tracking technology within the European sounding rocket program. Compared to radar, GPS offers an inherently higher absolute accuracy, a reduced data noise as well as the onboard availability of navigation and timing information [3]. Following successful application in a variety of sounding rocket flights, GPS has therefore recently been recommended as the baseline for range safety tracking systems both for cost and performance reasons and is expected to provide the primary sensor for flight terminations systems in the near future [4].

Difficulties in the use of GPS on sounding rockets stem from the high dynamics and the environmental conditions that necessitate special receiver and antenna systems. To reduce the dependence on US providers, dedicated antenna systems and a high dynamics GPS receiver (Fig. 3, [5]) have been developed in a joint effort of DLR and German industry. As part of the Texus/Maxus program these system components have demonstrated their performance and are now expected to find their way into a regular operational usage.

Fig. 3 GPS Orion-HD receiver for sounding rocket tracking and IIP prediction

As a third choice, inertial platforms can provide real time trajectory information for both onboard guidance applications and range safety support. An inertial measurement unit (IMU) is part of e.g. the Maxus guidance system that controls the flight path during the boosted ascent phase of this rocket. It performs simultaneous measurements of body-fixed accelerations and angular rates, from which the 12-dimensional translation and rotation state vector is derived by integration. Due to the complex sensor and computer hardware, precision IMUs are notably more costly than a GPS receiver

A careful calibration of gyro-drifts within am IMU is required prior to launch and any residual random walk or offset may ultimately result in erroneous trajectory estimates. On the other hand, the sensors are not affected by adverse R/F signal conditions. As such, IMU based tracking systems are insensitive to vehicle/antenna orientation, ionization, and jamming.

An optimum tracking system concerning accuracy, robustness and onboard availability is therefore obtained by merging IMU and GPS data into a common navigation solution. This concept has e.g. been applied in the BMRST range safety system for ballistic missiles developed by Honeywell Sapce Systems [6]. Whether or not the high overall system cost associated which such a system is justified for a particular flight must be decided on a case by case basis and depending on the mission criticality. For scientific sounding rocket campaign with a tight overall budget constraint, however, a GPS-only system can generally be considered to provide an excellent cost-performance ratio and – so far – a favorable reliability record.

2.2 Instantaneous Impact Point Prediction

Given the vehicle position and velocity at a particular instance, the subsequent flight path needs to be predicted up to its intersection with the surface of the Earth. Given the facts that the trajectory is typically confined to a small range area and that trajectory information is often available relative to the launch site, it has become customary to perform the IIP prediction in a local horizontal coordinate system. The motion of the rocket is then subject to apparent (Coriolis and centrifugal) accelerations caused by the non-inertial nature of this reference frame. For short flights the gravitational acceleration results in a parabolic trajectory, but in actual missions the altitude variation of the central attraction as well as the Earth's flattening have to be considered in the modeling. Furthermore, atmospheric forces affect the flight path during the late and early phase (typically below a 40 km altitude).

Even though real-time IIP prediction based on a rigorous trajectory integration is feasible today (at least on ground and with moderate update rates), one is typically interested in closed-form expressions that are less demanding in terms of processor need. Aside from Keplerian orbit models, various forms of perturbed parabolic models (see e.g. [7]) are therefore commonly applied in operational range safety systems. To comply with the increased tracking performance offered by e.g. GPS, a refined analytical IIP prediction method for real-time applications has recently been developed by the authors [8]. The model is based on a plane-Earth parabolic trajectory model with first order corrections for surface curvature, gravity variation and Earth rotation. Despite the implied simplifications the resulting model is more complete and of higher accuracy than conventional IIP algorithms based on a flat Earth approximation with Coriolis correction.

Due to its inherent simplicity the analytical IIP model is well suited for real-time time computations and has successfully been used inside the Orion-HD receiver [5] for IIP prediction during the Maxus-5 sounding rocket campaign. Comparisons have demonstrated that the overall agreement with a full modeling of conservative forces is high enough to introduce IIP prediction errors of less than 1.5% of the ground range for sounding rockets reaching altitudes of up to 700 km and flight times of about 15 min. This is certainly adequate from a range safety point of view and the model was even found to outperform the operational ground based IIP prediction software at Esrange [9].

2.3 Alert and Response

As shown above, accurate real-time IIP predictions (at least as far as the non-gravitational forces are concerned) can be today be performed either on ground or onboard a sounding rocket. In both cases, the existence of alternative tracking systems (radar, GPS, IMU) ensures that at least two independent sources of navigation information can be made available for redundancy purposes.

Based on the predicted impact point and a set of pre-established flight rules the range safety officer has to recognize a mission critical situation and decide on the need for a premature abort of the boosted flight phase. Provided that all criteria for a flight termination are clearly specified and described by associated conditions (including fuzzy rules), the decision can, in principal, be fully automated using machine based reasoning. In this way, the response time may be reduced and the potential for human errors can be minimized.

Given the availability of onboard IIP information, it appears only natural to further consider a fully autonomous flight termination system [4]. Here, all necessary decisions would be taken onboard based on GPS/IMU navigation information and applicable flight rules. In this way a redundant downlink or radar is no longer required, which offers an overall reduction of the space and ground segment complexity. Among others, a prototype version of an autonomous flight termination is presently studied at Kennedy Space Center (Bull priv. comm.). Extensive flight experience will, however, be required before a fully autonomous system becomes fully accepted and released for operational use.

3. MISSION RESULTS

Following the discussion of general system aspects, we turn to a presentation of flight results from recent sounding rocket launches. Where available, various sources of IIP information are compared and the achieved overall accuracy and reliability is discussed.

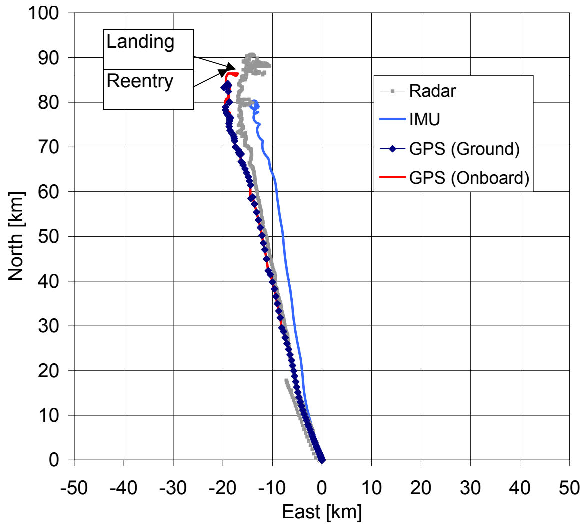

Fig. 3 Instantaneous impact point predictions for Maxus-5 using radar, GPS and IMU data

3.1 Perspectives …

The launch of Maxus-5 on 1 April 2003 marked the first ESA sounding rocket mission employing an operational GPS tracking system for range safety support. Two GPS receivers (Ashtech G12 HDMA and Orion-HD) with partly independent antenna systems were flown to achieve a maximum level of redundancy. Using position and velocity vectors from both GPS receivers, IIP predictions were generated on ground and used to validate a safe flight. Furthermore, onboard IIP predictions were generated by the Orion-HD GPS receiver on a non-operational basis. Ground based and onboard predictions agreed fully within the limitations of small algorithmic differences identified earlier [9].

Due to heavy ionization, temporary S-band telemetry dropouts were encountered near boost end, which resulted in a short loss of GPS navigation data on the ground. While of little concern for mission safety, this problem illustrates a potential benefit of an autonomous onboard flight termination system.

A comparison of GPS based IIP results with values predicted from radar measurements and the IMU of the Maxus-5 guidance system is given in Fig. 3. While the GPS state vectors provide an impact point prediction in close accord with the actual reentry and landing point, pronounced systematic errors are evident in the radar and IMU results. Despite its inherently lower system cost and operational complexity, GPS must therefore be considered as the most advanced tracking system for the Maxus rocket and will be used as prime sensor for range safety purposes in future flights.

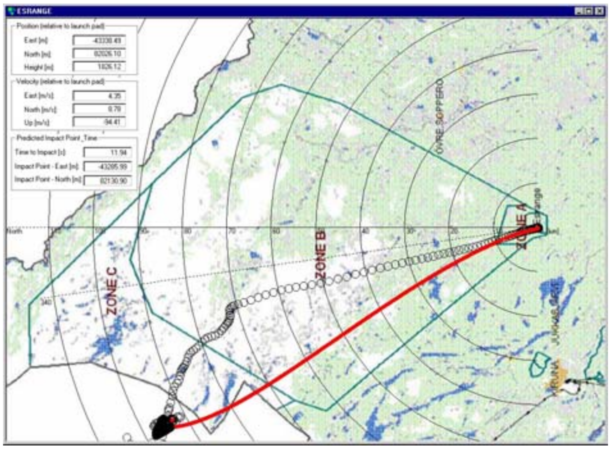

Fig. 4 GPS based IIP predictions (circles) and ground track (solid line) for Maxus-4. North is left and east up on this screen shot of the GPS real-time monitoring system.

For further reference, GPS based IIP predictions collected during the Maxus-4 campaign on April 30, 2001 are shown in Fig. 4. The rocket followed the nominal flight path for approximately 35 s of the 72 s boost phase. Thereafter, an increased west component of the thrust vector built up, which resulted in a sharp left turn of the instantaneous impact point. The online IIP prediction provided a rapid indication of the off-nominal performance of the guidance system and the landing point across the Norwegian border. Even though the predicted landing point was slightly outside the range boundaries it was known with good confidence due to the high inherent accuracy of the GPS navigation data. An immediate risk assessment and trade-off of available options therefore resulted in the decision not to destroy the rocket. Accurate IIP predictions thus helped to safe the mission and science operations in this particular contingency.

3.2 … and Limitations

The satisfying results discussed in the previous section should not, however, preclude the fact that IIP predictions are essentially limited by the restricted (or even) lacking capability for modeling atmospheric effects during the ascent and reentry.

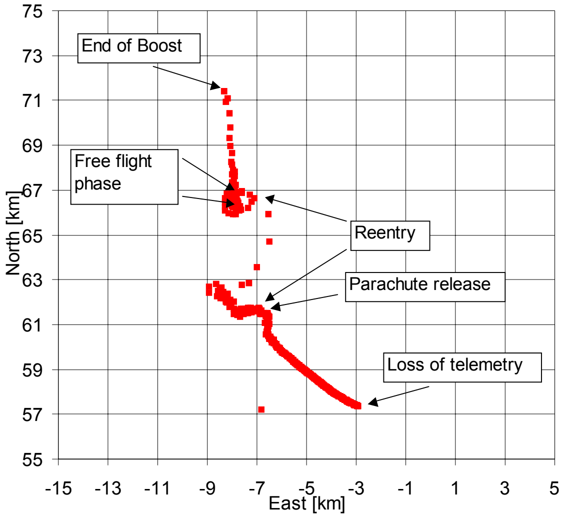

Fig. 5 Variation of GPS based impact point predictions for the Test Maxus-4 flight after burn-out of the motor.

Both effects are e.g. evident in IIP data from the Test Maxus-4 flight conducted on Feb. 19, 2001. The Improved Orion rocket achieved a peak altitude of only 80 km, which implies that a notable fraction of the overall trajectory was spent in dense parts of the atmosphere. After burn-out of the motor in an altitude of 20 km, a maximum IIP range of 72 km was predicted (Fig. 5). Thereafter, the IIP moved back south and converged to a stable location 66.5 km north and 8 km west of the launch site. The rapid change in the computed impact point is clearly caused by residual atmospheric drag between burn-out and an altitude of about 45 km, which is not accounted for in the common IIP prediction models.

Similarly, the computed IIP started to spiral away from the stable point as the payload entered the atmosphere again at the end of the free flight phase (h = 41 km) and started an erratic tumbling motion down to the parachute release. In total the IIP moved by roughly 5 km during the atmospheric reentry. Low altitude winds finally caused a south-east drift of the payload and the impact point by another 5 km prior to touch down.

While some progress concerning the analytical description of atmospheric IIP perturbations has been reported in [8], the resulting model is confined to the ascent phase and a stable flight configuration. Even under these constraints a general validation and accuracy assessment is pending in view of lacking calibration data from an extended set of missions.

An even more severe situation has been encountered during the VS30/Cuma mission launched Dec. 1, 2002 from the Alcantara launch site in Brazil. Here, extreme loads caused by strong winds and a thrust vector misalignment resulted in a premature opening of the manacle ring and a subsequent payload separation at the end of the boost phase. Thereafter, the payload started an erratic tumbling with repeated turn-overs caused by the lacking spin or fin stabilization.

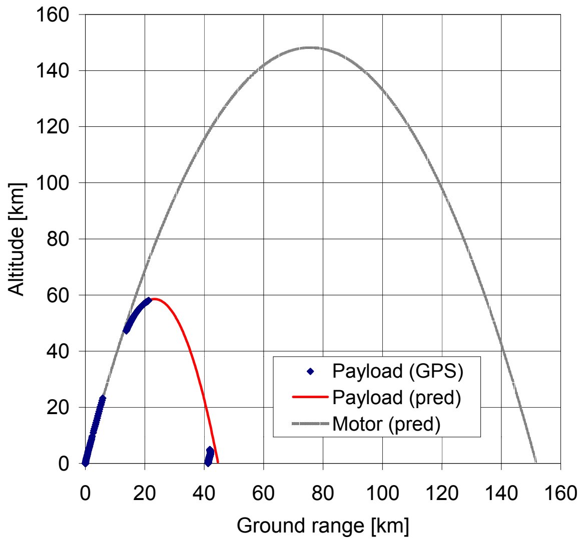

Fig. 6 Predicted motor (shaded line) and payload trajectory (solid line) following the breakup of the Cuma rocket. GPS based position measurements are indicated by diamonds.

As a result of its irregular orientation, and the low altitude (ca. 25 km) the payload experienced extreme drag forces after the breakup, whereas the motor roughly followed its envisaged flight path. While GPS tracking was lost for most of the "free-flight" phase, the available data show that the payload achieved an altitude of only 60 km and a ground range of 40 km as opposed to the nominal values of 150 km.

However, all IIP predictions provided by GPS tracking during the boost phase are based on the assumptions of low atmospheric drag and are only applicable for a stable flight attitude. In fact, a good agreement has been found between the actual motor landing point and the predicted IIP at burn out. The payload landing pointed, in contrast, is located at only 30% of the predicted ground range. This offset is clearly caused by a dramatically contingency but it remains unclear, how atmospheric forces would ultimately affect the impact point(s) in case of an intentional flight termination.

SUMMARY AND CONCLUSIONS

A summary of available tracking systems has been provided and flight data from various European sounding rocket missions have been used to illustrate the potential and limitations of present IIP prediction technologies.

Suitable analytical trajectory models and the use of GPS navigation sensors for high dynamics applications enable accurate predictions of the instantaneous impact point of a sounding rocket under nominal flight conditions. The availability onboard navigation sensors with IIP prediction capabilities is expected to gradually shift key elements of the range safety installations into the avionics and guidance system. This may ultimately enable a fully autonomous flight termination system that is independent of the ground facilities.

Despite these encouraging developments, the IIP prediction still suffers from an insufficient modeling of atmospheric flight phases which poses the most sever constraints to the achievable accuracy. While a limited progress has been made to describe the IIP shift caused by drag during the ascent trajectory, the ballistic properties of a rocket after a destruction or malfunction remain to a large extent uncertain.

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